

SCHOOL OF ENGINEERING SCIENCES AND TECHNOLOGY

DEPARTMENT OF FUELS AND ENERGY



CHINHOI UNIVERSITY OF TECHNOLOGY DPhil PROJECT

**Project Title: Design of a Concentrated Solar Thermal Power Plant for
Integration with coal-fired power stations**

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I, Tendai Peter Munyanduri, National I.D. No. 63-500515Y swear and Declare that this DPhil full Project is a product of my own research with guidance of my academic superiors Professor Musademba and Dr. Kapuya and also reference material as cited at end of the project and or references included within the body of the project.

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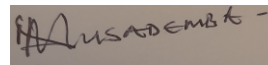
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Key Words and Their Definitions

Chemistry: is the study of matter and the changes it undergoes e.g. heat content change (enthalpic kinetics), phase change (phaseonic kinetics), color change (chromatic kinetics), smell change (Smellionic kinetics), changes in mass (massionic kinetics), changes in texture (texturionic kinetics), sound change when hit with a tea spoon (soundiotic kinetics) and change in taste (tastionic kinetics). The speed of phase change in Latent heat need to be accurately measured. The color change speed as indicating Thermochemical heat storage needs to be precisely ascertained.

Solar field: is the aggregated geographical space which is occupied by Heliostats. It is the largest factor for deciding in the design of a Concentrating Solar Thermal power stations.

An endothermic reaction this is any chemical reaction which absorbs or sucks thermal energy from its environment. Endothermic chemical reactions which are reversible can be used to store thermal energy or heat in tanks in Concentrated solar power plants.

An Exothermic chemical reaction is any chemical reaction which gives or emits light or heat to its environment. It is seen as being opposite to endothermic expressed as **Reactants → Products + Energy**

Thermodynamics: is the field of study that encompasses the motion of heat and conversion of thermal energy to work. In general, it is the interconversion of energy from one form to another (Kumar (1995)). Thermodynamics is a crucial area of study in Concentrated Solar power plants.

A system is in thermodynamic equilibrium if the system is in chemical, thermal and mechanical equilibrium (Kumar (1995)).

A system which is in thermodynamic equilibrium has all of its parts at the same temperature and also that temperature is identical to its surrounding.

Enthalpy: According to Blanco and Santigosa (2017), 'enthalpy is the total heat content of a system.

According to Blanco and Santigosa (2017), **The specific heat or heat capacity** of the substance is the quantity of heat required to alter the temperature of a given unit mass of the substance by 1(one) degree

Design: is the process of calculating, identifying, sizing, selecting and configuring the best components of a system and developing of engineering drawings of a system which is frequently done after due research and considerations in order to lower operational and capital costs and at the same time ensuring a quality product! (T.P. Munyanduri (2015))

A system: is an assembly of dependent components which by interacting achieves a specific objective like a Central Receiver Tower Power Plant (CRTPP).

Heat Insulating material: - These are materials which forbids or prevents the flow of heat within them. Major heat resistant materials are fibre board, cork, asbestos, glass, porcelain and reflecting paper etc. (Kumar (1995)). These materials could be employed as outside materials for pipes and Thermal energy storage tank.

Pyrometer: is an instrument or gadget for measuring high temperatures (Kumar (1995)). These will be employed in Thermal Energy Storage (TES) tanks and receivers.

Heliostats: are arrangements of mirrors which are guided by advanced computers that tracks the sun's movements such that the reflected radiation is always focused onto a receiver which will be stationary and installed on top of a very tall tower.

Concentration ratio:

Ratio of the total area of heliostat to the area of the receiver

Heat transfer fluid (HTF) in a CRS:

Fluid enclosed in the solar absorber or receiver that accepts and stores heat from the heliostats

Parasitic power, parasitic losses:

Power needed in order to make electric devices and pumps operational in a power plant.

Radiation:

propagation and emission of electromagnetic energy via material or space.

Receiver efficiency:

Ratio of the thermal output delivered by the receiver HTF to the incident solar radiant flux under reference conditions.

Solar absorber or Receiver:

A gadget that absorbs and intercepts solar radiation from the heliostat which is installed on top of a very tall tower. It raises the temperature of a heat transfer fluid (HTF).

Spillage, spillage losses:

A fraction of solar flux that strays away from the solar absorber when the receiver is aimed by heliostats.

ABSTRACT

There are problems of company closures, reduced standard of living for citizens, reduced capacity utilization of economic infrastructure and increased cost of doing business in Zimbabwe as a result of rampant and unprecedented blackouts caused by inadequate generation capacity. In addition, there are also climate goals setup by the United Nations COP 26 meeting which Zimbabwe with a lot of coal power stations must meet by reducing or eliminating carbon dioxide emissions from coal power plants.

There are many generation technologies which Zimbabwe can tap into to solve the above problems including fossil fuel generation (coal, gas and oil), nuclear, hydro, geothermal, thermoelectric, photovoltaic, piezoelectric, tidal, wave, wind, thermionic, parabolic dish, Linear Fresnel, parabolic trough and Central Receiver tower power generation schemes also called solar tower. Literature review on conventional and other generation technologies will be briefly carried out in order to place Concentrated solar power generation in context of other options in terms of disadvantages and advantages.

The thesis designed a 500 MW Power Tower power plant and demonstrated possible ways of integrating it with coal-fired power stations like Hwange, Munyati and Harare power stations in Zimbabwe. Yousef et.al. (2021) posits that integration of Central Receiver Tower (CRT) Power Plants with coal can reduce the cost of generated electricity by between 20-30 % that standard CRT power plants incur. Enkhbayar et.al. (2021) highlights that thermal to electricity conversion efficiencies of hybrid power plants i.e. solar-coal are greater than those of solar only generation at the same temperature. The Central Receiver Tower Power Plant is a type of a Concentrated Solar Thermal Power Plant. The Central tower was designed, solar absorber also designed followed by thermal energy storage tanks' design. The heat exchanger was then designed and choice of an appropriate generator and turbine set followed. The control building was designed followed by step-up substation design. The site plan of the said substation if it was to be implemented in Kadoma area in Zimbabwe was designed and drawn.

The thesis found out from literature that an average single tower Central Receiver Tower power plant has an overall plant efficiency of 20 %. Kayvani (2014) says that

the following forces need to be considered in the design of tall buildings like the Central tower: - (1) gravity effects (2) likely earthquakes (3) wind (4) lateral earth pressures which are unbalanced that could be imposed onto the foundation pad in any given direction.

It was found out that in order to increase the power tower plant efficiency, the following were crucial (1) Tracking which was dual-axis (2) An efficient receiver (3) The heat transfer fluid and working fluid paths had to be thermally insulated (4) The heat engine or power block had to be efficient and (5) Employment of highly reflective mirrors (96 % reflectivity). Alici and Turmay (2021) posits that the operation and maintenance costs for dual axis tracking is more compared to that for a single axis tracking system.

Most data for this project were obtained from google and Meteorological office e.g. solar radiation map of Zimbabwe, wind speed at Kadoma at 4m high, average temperatures and soil strength in Kadoma. These were the values used in the calculations.

The major findings were that (1) 500 MW Central Receiver Tower (CRT) power plant requires a lot of space 2.4 km by 2.4 km stand (2) multi-tower designs are more efficient but more expensive than single tower CRT power plants (3) coal-solar integration reduces intermittency and dispatchability of power generation in solar CRT power plants without enough heat storage or without storage. It was found out that solar-coal hybridization eliminates need for thermal storage.

THE SIZING OF STORAGE TANKS

Assumptions

- (1) The thermal levels of the heat transfer fluid are raised from 600 °C to 1000 °C by the receiver which is also called the solar absorber
- (2) There is need for supplying the electricity grid with 500 MW for 14 hours (2.25 x 10¹³J of storage is needed).

From the thermal energy storage materials' specific heat capacities, one can compute the mass needed to produce 500 MW. From the material density and the above, one could compute and quantify the volume needed for the thermal energy storage tanks. If we assume a tank of height 10 m, one can compute or quantify the radius of the required tanks as follows: -

SALT	SPECIFIC HEAT CAPACITY	MASS	DENSITY	VOLUME	DIAMETER (10M HEIGHT)
Sodium Nitrate	1371 J/kg K	42 254 583 kg	2260 kg/m ³	18 790 m ³	50 m(MODULARIZE)
Potassium nitrate	1118.5 J/kg K	51 793 504 kg	2110 kg/m ³	24 546 m ³	60m (Modularize)
Saturated sand	1 632 J/kg K	38 602 941 Kg	1 980 kg/m ³	19 497 m ³	50m

TABLE 25

Instead of one big tank, if one modularizes the tank to become 7 tanks, we will result in the following: -

SALT	DIAMETER
SODIUM NITRATE	1 tank 25m radius(too risky), or 7 tanks 10m radius or 30 tanks 5m radius
POTASium NITRATE	1 tank 30m radius, 9 tanks 10m radius or 40 tanks 5 m radius
SATURATED SAND	1 tank 25m radius(too risky), or 7 tanks 10 m radius or 30 tanks 5m radius

TABLE 26

Sodium Nitrate/Saturated Sand			Potassium Nitrate		
NUMBER OF TANKS	OF	RADIUS	NUMBER OF TANKS	OF	RADIUS
1		25	1		30
7		10	9		10
30		5	40		5

TABLE 27

LATENT HEAT

One can compute the needed mass to produce 500 MW from the latent heat of vaporization. One can compute and quantify the volume and hence size or dimension the thermal energy storage tanks from the material density.

MATERIAL	ENERGY PER KILOGRAM	KILOGRAMS REQUIRED	DENSITY	VOLUME	RADIUS assuming 10m high tank
MgCl ₂	1338 Kj/kg	2 072 000kg	2 320kg/m ³	894 m ³	5.35 m
KCl	5 960 000 Kj/kg	4 229kg	1 980 kg/m ³	2.1m ³	0.26m
NaCl					
NaCO ₃					
LiCO ₃					
KCO ₃					
KCL	31.31 kJ/kg	804 854 680 kg	1980 kg/m ³	406 493m ³	360m(not practical)

TABLE 28

MATERIAL	MELTING POINT	LATENT HEAT (Kj/kg)	SOLID SENSIBLE(Kj/kg)	LIQUID SENSIBLE(Kj/kg)	TOTAL HEAT (Kj/kg)
Magnesium Chloride	714 °C	454	0.1356	0.34023	454.48
Aluminum	660 °C	405	0.053	0.000055	405
Sodium Carbonate	851 °C	357	0.3396	0.2017	357
Lithium Carbonate	723 °C	45	0.1733	0.3902	45

TABLE 29

TANKS' VOLUME NEEDED FOR LATENT HEAT

PHASE CHANGE MATERIAL	Kg Required	Density	Volume	Diameter of Tank Assuming a 10 m high tank
Magnesium Chloride	55 506 608	2 320 kg/m ³	23 926 m ³	55m
Aluminum	62 359 276	2 700 kg/m ³	23 096 m ³	55m
Sodium Carbonate	70 743 716	2 540 kg/m ³	27 852 m ³	60 m
Lithium Carbonate	561 233 480	2 110kg/m ³	265 988 m ³	185m(not practical & lithium is very expensive)

TABLE 30

THERMOCHEMICAL HEAT STORAGE TANKS

One can compute and quantify the mass needed to produce 500 MW from the heat of reaction per mole. One can compute the volume of the required tank from the density of the material as follows: -

SALT	ENERGY PER KILOGRAM	KILOGRAMS REQUIRED	DENSITY	VOLUME	RADIUS(assuming 10m high)
CaCO ₃	14.52 kJ/kg	1 735 537 190.08	2 710 kg/m ³	640 419.63	142m(not practical)
LiBr plus H ₂ O	578.3 Kj/kg	43 575 999	3 460 kg/m ³	12 595m ³	21m
LiCl	-91.994 Kj/kg	2 739 310	2 160 kg/m ³	1 270m ³	6.4 m
CaCl ₂ plus water	656.8 Kj/kg-K	88 202	2 150 kg/m ³	17 845 m ³	24m

TABLE 31

The main solar-coal integration methods identified include (1) solar preheat and coal post heat (2) coal preheat and solar post heat (3) parallel steam path upto just before turbine (4) integration on the electricity busbar after the generator and (5) 2 different coal and solar power plants several kilometers apart feeding on the same grid. The integration method number 5 is the recommended method for the designed 500 MW CRT power plant. In solar CRT power plants integrated with coal generation, thermal heat energy storage may not be necessary because of ramping up and down

of coal power stations to suit weather variations and therefore to compensate for CRT power output.

The thesis concluded by highlighting policy implications of the research, contributions to the world body of knowledge and recommending areas for future research. The major contribution to the world body of knowledge includes (1) the fact that the thesis provides a comprehensive design for large scale solar thermal power plant and a practical framework for integrating it with coal power stations. It will add both qualitative and quantitative value to the field of Renewable energy engineering in the context of Southern African countries like Zimbabwe. (2) new methods of integrating solar and coal generation were proposed e.g (a) coal pre-heat and solar post heat (b) solar pre-heat and coal post heat (c) parallel steam path to just before the turbine (d) parallel steam path and electricity generation with electricity busbars being the point of common coupling (e) different and separate coal and Central Receiver Tower Power Plant power stations many kilometers apart feeding into the same grid. (3) The third contribution is that there are 6 states of matter (a) rock solid, (b) powder, (c) paste or thin porridge state, (d) liquid, (e) gas and (f) plasma when literature says there are only 3 states of matter.

The other contribution to Worldly Body of Knowledge include being able to measure the speed and velocity of latent storage dynamics e.g rate and speed of change of phase (phaseonic kinetics) and thermochemical reactions through chromatic kinetics (i.e. speed of color change as an observable dynamic which indicates that a chemical reaction has started and when it stops), enthalpic kinetics (rate, speed or velocity of heat acquisition and heat release) e.t.c.

Areas that need improvement in future include enhancing the overall plant efficiency and embracing National financial allocation policies that favor power generation to be able to sufficiently rise up to the challenges it is currently facing.

CHAPTER ONE

INTRODUCTION

1.0 Background & Introduction

Although Chang (2007) says that the main sources employed in the production of electrical power are in the fossil fuels group (i.e. petroleum, coal and natural gas) whose reserves are estimated to last for the next 50 to 100 years at the current rate of use, research has identified 22 electricity generation methods as follows: -

1. Fossil fuel generation (coal, natural gas and oil)
2. Nuclear
3. Hydro
4. Photovoltaic
5. Wave generation
6. Tidal electricity generation
7. Thermoelectric
8. Geothermal
9. Wind
10. Concentrated Solar Thermal power generation schemes which are as follows
 - (a) Solar Power Tower also called the Central receiver Tower Power Plant
 - (b) Linear Fresnel
 - (c) Parabolic Dish
 - (d) Parabolic Trough
11. Ocean thermal energy conversion
12. Ocean salinity gradient -osmotic generation
13. Ocean currents generation
14. Greenhouse gas generation
15. Thermionic-or heat generation
16. Piezoelectric-pressure on quartz crystals
17. Magneto hydrodynamic
18. Employing solar flux to extract hydrogen from water and feed the free hydrogen into a fuel cell in order to produce electric power (Chang, 2007)
19. Using a rectenna (antenna and diode) to convert electromagnetic waves to d.c. current
20. Biomass
21. Chemistry e.g. batteries

22.Friction

Items 3 to 14 are renewable energy generation methods and 1 to 3 are conventional electricity generation methods. The above energy sources produce varying quantities of electricity with different efficiencies with some being capable and some incapable of producing electric power in large quantities suitable for supplying power utilities' grid needs.

There are technical complications of retrofitting solar generation to coal power plants in that the frequency of both sides need to be the same and synchronized as well as the voltage levels need to be the same. Variability of solar irradiance and land availability is a challenge.

Challenges facing Zimbabwe are: -

- (1) Variable weather and sunlight conditions especially during rainy seasons
- (2) Frequent droughts which make hydro-generation unreliable year after year
- (3) Depleting coal resources used for coal generation
- (4) Lack of suitable sites for geothermal generation
- (5) Lack of skills for nuclear generation
- (6) Zimbabwe is a landlocked country which rules out Tidal and Wave generation
- (7) Lack of skills for Concentrated solar generation
- (8) Adverse climate change e.g. 'Cyclone Idai' which resulted in several deaths
- (9) Bad relations with Western countries which retards knowledge transfer

Opportunities facing Zimbabwe

- (1) Plenty of sunshine making solar generation viable
- (2) Abundant coal reserves making coal generation attractive
- (3) Highly educated citizens
- (4) Plenty of educational institutions
- (5) Availability of uranium which can be used for nuclear generation which has not yet been exploited
- (6) Good relations with Eastern Countries which can enable skills transfer
- (7) Windy conditions especially during the months of July and August making wind generation slightly viable

The project will try to mainly focus on Central Receiver Tower Plant (item 10) design and less on Coal power generation and integration techniques in order to focus on the intention of the topic. Other potentially viable generation techniques to Zimbabwe will be briefly covered.

Chang (2007), says that it is estimated that by 2050, 50 % of the global village's electric power needs would be supplied from sunlight energy and hence sunlight energy is promising to be a highly viable electrical energy source for satisfying future energy needs. In the following fifty years, nuclear fusion would most probably be a source of electricity that is significant (Chang, 2007)

According to Freris and Infield (2009), the percentage contribution of various generation types used in the generation of electricity globally are as follows: -

<u>NUMBER</u>	<u>ENERGY SOURCE TYPE</u>	<u>% Contribution</u>
1	Hydro	19 %
2	Nuclear	16 %
3	Coal	39 %
4	Oil	10 %
5	Gas	15 %

TABLE 1

All the other generation methods were contributing 1 %. In Zimbabwe only hydro-generation, coal generation and solar photovoltaic have been exploited and the rest are still unexploited.

According to DLA Piper (2028), the contribution of various sources of energy in Zimbabwe is as follows in 2022: -

ITEM	ENERGY SOURCE	PERCENTAGE
1	Hydropower	68.17
2	Coal	31
3	Renewables	0.83

TABLE 2

The table above shows that coal generation constitute the bulk of the generation output in Zimbabwe.

Recurrent drought in countries like Zimbabwe compromises hydro generation in years of drought.

Mathew (2022) posits that the combustion of fuels of the fossil fuel type like coal has led to greenhouse gases' emission into the atmosphere. Gases that trap thermal energy or heat within the atmosphere are called 'greenhouse gases'. According to Mathew (2022) examples of gases that are greenhouse encompass Nitrous oxide N_2O , carbon dioxide CO_2 , and CH_4 . These gases possess and have the same results as when one leaves a vehicle in hot weather with windows closed. After a lot of time of exposure to the sun, the inside of the vehicle will be hotter than the outside. The burning of fossil fuels gives rise to an increase of atmospheric temperatures which in turn gives rise to the melting of ice at the South and North poles of the earth which threatens sea port towns and islands. People and animals within these ecosystems are displaced from such areas where the sea level rises. CO_2 and N_2O are the byproducts that result from the burning of fossil fuels whilst methane NH_4 is released during the transportation and production of coal.

According to McKinsey and Company (2024), power generation contributes approximately 30 % of global CO_2 emissions and this is mainly from fossil fuel generation and transportation needs

The ozone(O_3) layer or ozone shield is a protective layer of gases that exists in the stratosphere portion of the atmosphere i.e. 15-35 km measured from the surface of the earth.

The most dangerous parts of the radiation from ultraviolet that is radiated from the sun is absorbed by the ozone layer. This dangerous radiation which is absorbed by the ozone layer would otherwise result in (a) immunity suppression within people

(b) damage to the human and animal genes (c) eye cataracts (d) skin cancer. The ozone layer's thickness changes geographically and seasonally.

Research has exposed the fact that ozone layer depletion was occurring as a result of chemicals produced by industry chiefly chlorofluorocarbons. The color of ozone gas is bluish.

Chang (2007), says that the main disadvantage of fossil fuel combustion to generate electricity includes the release of carbon dioxide (CO₂), that is a well-known gas that belongs to the greenhouse family of gases alongside with nitrogen oxides and Sulphur dioxide that give rise to smog and acid rain.

Houghton (2009) posits that the climate system's warming is indisputable as it is now evidenced by increases in the world's average ocean and air temperatures that is observed and melting of polar ice and snow that is widespread and the rising of ocean and sea levels.

According to Freris and Infield (2009), 'the change in Climate conditions poses danger to human life, flora and fauna e.g. availability of food and water, healthy living, optimal use of land and the environment which become threatened. If action is applied now, the worst impacts of the change in climate could be prevented and averted in future. There is a compelling need for an international response implemented through the United Nations. This response could be through social pressure on member countries. Planet earth could become uninhabitable futuristically if preventive and corrective action is not taken now. The atmospheric climate may not be able to facilitate, sustain or support life in future if the world's population does not confront this threat collectively. The Conference of Parties (COP) 26 meeting resolved that there was need to decommission coal power plants.

According to Mathew (2022), global warming or climate change is felt by the following developments: -

- Frequent droughts
- Heat waves
- Wild fires that are frequent
- Melting of snow and ice sheets at the poles of the earth e.g. North and South poles resulting in rising of sea levels.

- Weather conditions that are extreme
- The sea levels rising by dozens of meters

Climate change or global warming is being caused by greenhouse gases mainly from electricity production using fossil fuel (i.e. natural gas, oil and coal).

According to Freris and Infield (2009) the key actions should include: -

- Massive exploitation of renewables, including other known low carbon options.
- Enhancement in energy use efficiency
- Transition to little carbon emission developmental trajectory
- Exerting pressure on nations that produce a lot of carbon dioxide through electricity generation through a series of COP meetings.
- Regulation or rules that promote solar rooftop solutions and efficient use of electricity.
- Enhanced Research and Development investment.

Solar generation has emerged as a crucial generation option due to concerns about environmental cleanliness, climate change considerations and need to ensure sustainability in the exploitation of energy resources. The sun being an infinity source of energy, Zimbabwe could benefit from such a source of huge quantities of clean energy

According to Nelson (2011), ‘The concentrations of global atmospheric carbon dioxide, nitrous oxide and methane have skyrocketed significantly as a byproduct of activities by human beings since 1950 and now surpass pre-industrial value.

Mathew (2022) says that the gases that are greenhouse and are primary within the earth’s atmosphere are methane, fluorinated gases, carbon dioxide and nitrous oxide. Since 1970, electricity production in industry have contributed about seventy percent of the total emission of greenhouse gases. 76% of the total greenhouse emission of gases is CO₂ and 24 % is other greenhouse gases (Mathew (2022)).

Fossil fuel use have primarily enhanced global concentration of carbon dioxide. The 1996 Kyoto Protocol agreement was focused on suppressing greenhouse emissions of gases and became effective in the year 2005 with Russia becoming the 55th country that ratified the agreement (Nelson,2011).

The participants had the aim of having collective greenhouse gas emission reduction of 5.2 percent below the levels of emissions in 1990 by 2012.

According to Nelson (2011), ‘the Arctic is thawing, due to high levels of a more dangerous gas than carbon dioxide belonging to the greenhouse family of gases called methane which would raise warming globally further.

Rising thermal levels which are caused varying climate have given rise to the rising of sea levels that is displacing people and animals’ habitant in those lands.

According to Blanco and Santigosa (2017),’using fossil fuel has caused climate change, air pollution and emissions of greenhouse gases and the resource is depletable.’

According to Sorensen (2011),’ the keenness in renewable energy is closely related to the warming of the earth’s atmosphere, which is aggravated by the increased release of greenhouse gases within the atmosphere.... injection of particulate matter with different sizes, and emission of chemical pollutants into the atmosphere at various levels. All of these have resulted in alterations in climate and atmosphere protection budget.’

According to Dorf and Bishop (2014: p25), ‘issues such as waste management, climate change, clean water, minimizing of raw materials, sustainability, emission reduction and energy use have resulted in many engineers rethinking existing approaches to engineering design in certain areas. As noted by Nelson (2011), there is need to shift to renewables, as a mitigatory measure to reduce release of gases which are greenhouse and simultaneously reduce environmental pollution.

The aim and objective of green engineering is to come up with products that lower pollution and at the same time lower risks to people’s health and enhance environmental and atmospheric protection.

As noted by Dorf and Bishop (2014: p23), 'It was estimated that deployment of smart grids could reduce CO₂ emissions globally by 14 % by 2020.' According to Blanco and Santigosa (2017), 'Reducing the bulk of the greenhouse gas emission globally needs to substitute fossil fuels with forms of energy that is renewable in industrial sectors, transportation as well as in the electric energy generation.'

According to Freris and Infield (2009), 'communities are currently heavily dependent on fossil fuel use. It is therefore unrealistic to wean these people from fossil use in the short term. For electricity and heating, the general trend is a shift from fossil fuels towards use of gas and to a lesser extent oil in place of coal. This has arrested the growth of CO₂ emissions since there is less CO₂ released during use of gas than coal. A possible option is to revert back to coal dependence. Coal exists in abundance in many developed countries inclusive of U.S.A., Canada, Australia, Russia and countries like Turkey, China and Zimbabwe. Latest developments in carbon dioxide sequestration or capture for coal, gives some positive hope that fossil fuels could become environmentally friendly

It has been found out that Concentrated Solar Thermal schemes give obvious advantages over PV electricity generation as well as over wind electricity production. Concentrated Solar Thermal could be integrated with heat storage schemes for enhanced load shifting and dispatch ability. Moreover, thermal energy storage reduces the levelized cost of electricity(LCOE) as a result of increased capacity factor which allows generation even during the time when the sunlight is non-existent due to night conditions and or as a result cloud cover. Therefore, CST power plants coupled with heat storage schemes (ESS) plays a significant role in renewable energy portfolio as load following or peaking plant. Heat can better be saved than electricity in batteries. Thermal energy storage systems can be generally categorized into 3 types: -

- (1) sensible heat storage(SHS)
- (2) latent heat storage(LHS) and
- (3) thermochemical heat storage

Coal power plants contribute to (1) climate change (2) diseases like pneumoconiosis and other lung illnesses in workers due to coal dust (3) environmental pollution when used coal is disposed (4) coal is a depletable resource and is non-renewable and hence considered for decommissioning worldwide.

The United Nations Conference of Parties (COP 26), resolved to (1) phasing down electricity production using coal (2) by 2050, to achieve carbon neutrality so as to keep global warming to be under 2 OC for example 1.5 OC relative to preindustrial times (3) step up investment in renewables (4) reporting on progress made towards atmospheric protection at the next COP 27 meeting which was later held in Egypt. China made a commitment to halt financing coal electricity production worldwide. Focus and attention was directed at third world countries like Zimbabwe and also China who had significant coal generation. They were urged to take climate protection seriously.

Wind and solar are on top as the most affordable and quickest growing sources of clean electricity (Mathew, 2022)

Most of Zimbabwe's power stations are coal based namely Munyati (120 MW), Hwange (1520 MW), Bulawayo (90 MW) and Harare (90 MW). This means Zimbabwe was adversely affected by the COP 26 resolutions. In response Zimbabwe decommissioned Munyati, Harare and Bulawayo coal thermal power plants. It has been reported in newspapers that Harare, Bulawayo and Munyati power stations were decommissioned in the year 2024. The research gap was found to be (a) a design template for a 500 MW solar tower power plant suited for Zimbabwe. (b) how to decommission coal power plants in Zimbabwe seamlessly without causing power insecurity which paves the way for the need of conducting this project research.

1.1 Statement of the Problem

At the present moment, Zimbabwe is faced with unprecedented power outages. The electricity shortages have been previously met with power imports which have now become erratic and unreliable. The United Nations COP 26 resolutions included scaling or shutting down of coal generation. The above situation means that if the

coal power plants are decommissioned without alternatives, Zimbabwe will be in total darkness. The problem being solved or minimized by this thesis is '**electricity inadequacy resulting in reduced National standard of living and complexities of integrating solar with coal generation**'. This threat paves the way for solar power plants as well as other renewables.

Problems of integrating coal power plants with solar includes ensuring same frequency through proper design and synchronization and same voltage output through prudent designs and phasing at the points of common coupling.

The variability of solar flux and problems of land availability in Kadoma which is a mining and agricultural town adds to the complexities. There is also the problem that thermal storage, grid integration and site specific problems in Kadoma in Central Receiver Tower (CRT) Power plants adds extra costs to the capital and operational costs of the CRT power plant thereby negatively impacting on its financial and economic viability. The complexity of solar thermal generation presents a technical barrier to integration.

Zimbabwe needs to be energy self-sufficient and reuse many useful equipment from the coal power plants if they are eventually decommissioned. According to climate justice (n.d.) Maximum installed electricity generation capacity in Zimbabwe is 2 540 MW as of 2021 with 1 400 MW coming from coal power plants. But because most of the generation equipment is old resulting in frequent breakdowns, droughts affecting hydro power stations and maintenance has resulted in available generation going down as far as 800 MW against an estimated National demand of 2500 MW. The resulting blackouts and rampant load shedding has resulted in the problems of company closures, reduced standard of living for citizens, inconveniences to tourists and reduced capacity utilization of economic infrastructure etc.

The stakeholders affected by blackouts include Commercial companies, mines, agricultural ventures, industries, citizens of Zimbabwe and tourists and visitors.

Frequent electricity blackouts and load-shedding is a deviation from the norm. The knowledge gap that exists is a detailed template design of solar thermal power plants suited for Zimbabwe. The ideal situation is whereby every person in Zimbabwe gets electricity supply whenever s/he needs it. The problem is emanating from very old power stations. In the middle of this dissertation Harare (120 MW), Munyati (120

MW) and Bulawayo (100 MW) power stations were decommissioned reducing the installed capacity in Zimbabwe to 2 200 MW against an estimated demand of 2 500 MW.

There is therefore need to build new power stations and modernization of the old power stations. The research gap is the availability of a template or methodology of designing a 500 MW Concentrated solar thermal power plant of the CRT type suited for Zimbabwe.

1.2 Aim of The Research

The aim of the project is to design a 500 MW Concentrated Solar Thermal Power Plant of the Central Receiver Tower type also called the Solar Power Tower Plant for integration with coal-fired power stations

1.3 Objectives

1. To research on coal generation, its advantages and disadvantages.
2. To design the various components of the 500 MW power tower power plant also known as the Central Receiver Tower Power Plant.
3. To show how to integrate Central Receiver Tower Power Plants with Coal power stations
4. To show how coal-solar integration resolves the intermittency and power dispatchability in Zimbabwe and neighboring countries.

1.4 Research Questions

1. What are the disadvantages and advantages of coal electricity generation?
2. How do we design the major parts of a solar power tower power station also called the Central Receiver Tower Power Plant?
3. How do we integrate solar Central Receiver Tower (CRT) power plants with coal power stations?
4. How does coal-solar integration resolves intermittency and power dispatchability in Zimbabwe and neighboring countries?

1.5 Justification of the Project

There is frustrating, crippling and unprecedented electricity blackouts in Zimbabwe.

The United Nations Conference of Parties 26 (COP 26) has urged for the decommissioning of coal thermal power plants on which Zimbabwe is heavily dependent. If this is done without alternative energy sources, Zimbabwe will be in total darkness. Power tower power plants alternatively called Central Receiver Tower Power plants can mitigate this eventuality and threat. Some components of coal power plants can be salvaged and be reused in solar thermal power plants.

The frontend of coal generation and power tower technologies are different, but the backend is the same. Power tower power plants are a viable replacement of coal power plants on the long term. Solar thermal power stations could be run round the clock because of heat storage tanks, but their efficiencies rely on weather conditions which are normally highly variable.

Thermal energy storage assists power tower power plants to adjust power production to suit weather and grid conditions and are therefore more flexible than Photovoltaics power plants. Heat can be stored more efficiently than electricity in batteries therefore these power tower power plants can be run day and night irrespective of the randomness of sunlight, season of the year, time of day, humidity and cloud cover. This gives advantage over P.V. which may only generate electricity during the day as it is more difficult to economically store electricity in batteries.

It is therefore imperative that this project and thesis be done to help the Zimbabwe Electricity Supply Authority (ZESA) prevent the power crisis. The project is therefore justified given Zimbabwe's electricity situation.

1.6 Significance of Study

The research will contribute towards electricity adequacy in Zimbabwe. In addition, there will be contribution to the world body of knowledge in terms of the 8 dimensions of Reaction Dynamics and chemical Kinetics such as chromatic kinetics (change in color), Smellionic kinetics (change of smell), phaseonic kinetics (change

in phase), soundiotic kinetics (change is sound produced when hit with an iron object), massionic kinetics (change in mass), enthalpic kinetics (change in heat content), tastionic kinetics (change in taste), texturionic kinetics (change in texture)- i.e. 8 possible changes that may be brought by a chemical reaction and how to measure all 8 of them as contribution to world body of knowledge. There will also be an attempt to device a methodology of trapping, processing and exploiting lightning green energy for commercial use as contribution to world body of knowledge.

1.7 Project Scope

The project will briefly discuss conventional and solar generation methods and then goes into the detailed design of a 500 MW Power Tower Power Plant and show how to integrate it with coal generation schemes. The bulky of the thesis will be devoted to the design of the solar thermal power station and a very small section to demonstrate how to integrate the designed type of power station with coal power plants.

1,8 Thesis Structure

Chapter one covers the background and introduction to the study and introduces the problem being addressed by the thesis including Aims, objectives, research questions and justification for undertaking the project.

Chapter two concerns literature review section which gives perspectives from literature on conventional generation, solar thermal generation and the Central Receiver Tower Power Plant

Chapter 3 is the methodology which also includes proposed journal papers on the design of a 500 MW Central Receiver Tower Power Plant and the actual design. It highlights that data was obtained from google and google scholar as well as other journal papers. Mathematical tools were used to process and analyze data. Ethical considerations such as making effort to eliminate or reduce plagiarism are mentioned.

Chapter 4 includes published papers

Chapter 5 includes findings of the thesis

Chapter 6 involves discussions and interpretation of results

Chapter 7 involves Summary of thesis

Chapter 8 involves conclusions and contribution to world body of knowledge and areas for future research

1.9 Research Methodology

The reason for carrying out this thesis is to gain knowledge which will contribute towards the world body of knowledge as well as assist in solving Zimbabwe's power crisis.

Knowledge was gained via a research process. According to McBurney and White (2010) there are two types of research methods available to a researcher namely (1) experimental and (2) non-experimental research methods. Experimental research involved designing and making a prototype and non-experimental research involved information from libraries, journal papers, google scholar, general google and information from visiting Munyati and Harare power stations. Also included amongst the non-experimental research techniques are case study method,

Knowledge could also be extracted from lecturers by being taught or supervised. This research technique was exploited exhaustively as guidance of supervisors were sought throughout the project period.

The knowledge in this thesis is grounded on facts and information trapped, processed and harvested from (1) literature review (2) knowledge from academic celebrities (3) cumulative practical experience in the power industry and (4) meditation, productive thinking, progressive thinking and creative thinking throughout the duration of this project.

RESEARCH METHODOLOGY	WHERE THE RESEARCH WAS CARRIED OUT	TIMING	PROGRESS TODATE
Desk Research- Primary Archival Research	Harare City library, University Of Zimbabwe Library, Chinhoyi University Library	May 2022 to March 2025	Already completed
Positivism	Calculations & Designs in my Office	August 2023 to June 2024	Already completed
Secondary Observational- Research	Centragrid Power Station, Harare Power Station and ZPC	to June 2024	Already Done

TABLE 3

The thesis now proceeds to do and analyze the theoretical framework on which the project is pivoted on.

Heliostat design was done using information from google. Information for tower, heat energy storage tanks, heat exchanger was obtained from previously taught and learnt at form 6, first degree and Masters' degree-i.e. cumulative previously internalized knowledge.

The equation $mc\theta = 500 \text{ MW}$ equation where m =mass, c =specific heat capacity or latent heat of vaporization or heat of reaction was key in the design of thermal energy storage tanks, receiver, heat exchanger and condenser.

1.10 THEORETICAL FRAMEWORK

According to Chang (2007), the study of matter and the changes it undergoes is called **Chemistry**. Atkins (1994) says that **Thermodynamics**: is the study of the transformations of Energy. This project is mainly about studying and calculating transformations of sunlight into heat and heat into pressure due to expansion of water from liquid to gas and pressure into rotational mechanical power and rotational mechanical energy into electrical energy. This implies that the project is based on thermodynamics.

A hypothesis is a tentative explanation for a set of observations summarizing the information in a concise way as a law (Chang, 2007)

Oxtoby et.al. (2008) says that a **hypothesis** is a new idea that is temporarily accepted. The hypothesis is then exposed to thorough testing in special experiments that will be strictly controlled. If the hypothesis survives numerous such tests, it is uplifted so that it becomes a **scientific law**. Oxtoby et.al. (2008) posits that a scientific law is predictive as it is always obeyed under same conditions.

Chang (2007) posits that **a law** is a concise mathematical or verbal statement expressing a relationship that exists between phenomena that will always be the same under the same conditions.

Chang (2007) explains that a hypothesis which remains valid and remain unbroken when numerous experimental tests are carried out may graduate into a theory.

Chang (2007) emphasizes that **a theory** is a unifying principle that explains a body of facts and/or those laws that are based on them.

Atkins (1994) alleges that the force that drives chemical and physical change is entropy which determines the spontaneous direction of change e.g. in chemical reactions.

The whole of this project is mainly pivoted on a number of laws which are the following:

- The law of conservation of energy

- The First Law of Thermodynamics
- The Second Law of Thermodynamics and
- The Third Law of Thermodynamics
- The law of reflection

The Law of conservation of energy states that energy can neither be created nor destroyed but can be transformed, converted or changed from one form to another or from one form to other numerous forms of energy. This law was used when we assume the heat energy $(Q)=mc\Theta$ in designing energy storage tanks, receiver, condenser and heat exchanger. In these designs we assume that all the heat energy was transformed to electrical energy without energy being destroyed in the process.

Input energy in one form(heat) =output energy in another form or forms (electrical energy). $mc\Theta=500 \text{ MW}$. This equation would not be valid if there was no law of conservation of energy.

Where m =mass of heat transfer fluid or working fluid

C =specific heat capacity, latent heat of vaporization or heat of reaction.

$\Theta=565^\circ-20^\circ\text{C}$ (i.e. plant average operating temperature minus atmospheric temperature)

The law of Conservation of Energy was discovered by James Prescott Joule who was a British physicist. Thermodynamics is the science of study concerning relationships between temperature, heat, work and energy. It deals with the interchange of one form of energy into another.

Energies in the form of heat, mechanical and electrical are interchangeable. The law of conservation of energy will apply on the receiver when light energy is converted to heat, it also applies when heat is converted to pressure and hence the rotational kinetic energy of the turbine-generator set and when the generator converts rotational energy to electricity. Atkins (1994) says that the principle of conservation of energy can be used to assess the energy changes that accompany chemical and physical processes. Energy transactions at each component of the Central receiver Tower Power plant can be quantified accurately.

The First Law of Thermodynamics states that in a closed and isolated system, the aggregated energy that a system possesses remains constant although it can be converted, changed or transformed from one given form into other form or forms. This law was employed when heat from a receiver is assumed to be the same as that in heat storage tanks and same as in the heat exchanger. This law is used due to the fact that if we insulated thermal energy storage and pipes we create a closed system so that there is no or minimum heat loss to the atmosphere. The heat energy therefore remains constant from receiver to thermal tanks to heat exchanger. This law is assumed and is key in the design of the CRT components above.

The Second Law of Thermodynamics states that thermal energy or heat will always invariably and spontaneously flow from a hotter region to a relatively colder region in matter. This law makes it imperative to insulate thermal energy storage tanks and all pipework where heat transfer fluid and working fluid before turbine flows otherwise heat energy will be lost to the atmosphere.

The first and second of thermodynamics was first expressed and stated by a German physicist Rudolf Clausius in about the year 1860. Walther Nernst who was a German Chemist stated the third law of thermodynamics around the years between 1906 and 1912.

The laws of thermodynamics will apply on and in energy tanks and the receiver also called solar absorber. They also apply in the heat exchanger, condenser and cooling tower. When the insulation is applied on the outside of transmission tubes/pipes, the law of thermodynamics will also apply. In condenser and Cooling tower where we want to lose heat to the atmosphere we do not use insulation.

The Law of Reflection

According to Ashish (2018), when a ray of light hits a surface, the angle of incidence is always equal to the angle of reflection, the two angles being demarcated or separated by the normal to the mirror.'

The law of reflection will operate within the heliostat mirrors when light is being reflected and refocused onto the solar absorber which is also known as the receiver. This law is also used in the design of the solar tracking heliostats dynamics and in the prototype design. The law is key in concentrating sunlight from a very large surface areas of heliostat mirrors to a small area on the receiver. Raised 'concentration ratios' as a result of the law of reflection ensures increased power plant efficiency.

Newton's Laws of Motion

Newton's First Law of Motion states that every body or entity will remain forever at rest or forever in constant motion in a straight line unless compelled, acted on or acted upon by an external force to act otherwise (Abbott, 1989). This law will apply when the blades of a turbine are hit by steam that will be under pressure. It will also apply when the generator is moved by the rotating turbine.

Newton's Second Law of Motion states that the rate of change of momentum of a body is directly proportional to the applied force and takes place in the direction in which the force is applied (Abbott, 1989). i.e. $F=ma$ where F =Force, m =mass and a =acceleration. This law will apply when the steam hits the turbine blades.

Newton's Third Law of motion states that for every action there is an equal and opposite reaction. Whenever a force acts on one body, an equal and opposite force acts on some other body (Abbott, 1989). This law explains why the turbine rotates when hit by the velocity of steam-i.e. steam impact on the turbine blades.

Law of Conservation of Momentum states that when 2 or more bodies act upon one another, their total momentum remains constant, provided no external forces are acting (Abbott, 1989). The law of conservation of momentum applies on steam impinging on turbine blades.

Fleming's Right Hand Rule (dynamo rule): Extend the thumb, forefinger and second finger of the right hand mutually at right angles, if the forefinger points in the direction of the field and the thumb in the direction of the force/motion, then the second finger will point in the direction of the induced current (Abbott, 1989).

This rule applies in the generator.

Newton's laws of motion will apply to the turbine-generator set including the steam hitting against turbine blades.

Fleming's right hand rule including Laws of magnetism will apply in the generator set e.g. like poles repel and unlike poles attract.

Coulomb's Law: The force exerted by one-point charge on another acts along the line between the charges (Tipler and Mosca, 2008). According to Tipler and Mosca (2008), this force varies inversely as the square of the distance separating the charges and is proportional to the product of the charges. The force is repulsive if the charges have the same sign and attractive if the charges have opposite signs (Tipler and Mosca, 2008).

The above Laws will assist in the calculations needed in the project, thesis or dissertation. These laws form the basic assumptions in the design of the CRT power plant

1.11 CONCEPTUAL FRAMEWORK

The thesis is premised on the following 11 concepts.

- (1) Spillage losses can be reduced by better focusing of sunlight from the heliostat mirrors to the receiver and also aiming the sunlight onto the centre of the receiver.
- (2) The optical efficiency of mirrors need to be improved for enhanced power plant efficiency
- (3) Calibration of the heliostats is also necessary for better control and focusing of the heliostats
- (4) The furthest mirror need to subtend a receiver angle of $13,5^{\circ}$ for acceptable atmospheric attenuation of solar flux on the journey from the mirrors to the receiver of sunlight.
- (5) If sunlight is concentrated from a very large surface area of mirrors to a far smaller area of the solar absorber through reflection, the temperature on the solar absorber can be increased even upto 1000°C .
- (6) When water is converted from the liquid phase to gaseous phase it expands about 1 700 times in volume thereby generating a lot of pressure if channeled through thin nozzles onto the blades of a turbine.
- (7) If you rotate a copper coil (i.e. a generator in our case) in a magnetic field, a current is generated as indicated by Fleming's Right Hand Rule.
- (8) Energy can be stored in the form of heat in thermal energy storage tanks.
- (9) Sunlight can be converted to heat and heat can be converted to pressure and pressure to rotational mechanical energy and rotational mechanical energy can be converted to electricity.
- (10) Electric pumps can enable transmission of fluids and therefore heat contained therein from one place to another through pipes or tubes.
- (11) The temperature of the thermal energy storage fluid and the working fluid must be below the melting point of the material used to make the fluid transmission pipes or tubes.

The project now proceeds to do a literature review starting with literature review on conventional generation and then literature on PV and solar thermal generation. Literature review on conventional and other generation methods will be done in order to appreciate their advantages and disadvantages compared with Concentrated Solar Thermal Power generation techniques

CHAPTER TWO

2.0 Literature Review On Conventional Generation

The project will discuss alternative conventional and non-conventional generation methods, their advantages and disadvantages before discussing Central Receiver Tower Power generation schemes in order to make the audience of this thesis be able to place Power Tower generation technologies within context of other generation technologies.

Coal generation and Nuclear generation are covered in the Published Papers Section. The project now proceeds to discuss hydroelectric generation as a generation option.

2.1 Developments in Hydroelectric Power Plants

INTRODUCTION

This section discusses hydroelectric power generation and highlights its advantages and disadvantages compared to other electricity generation methods. The section posits that hydroelectricity is a non-polluting (i.e. clean), efficient and renewable source of energy.

Hydroelectric power generation converts the linear kinetic energy of moving waters in rivers into gravitational potential energy, then kinetic energy which is later transformed into electrical energy through employing turbine-generator sets. The section highlights that the higher the head and the greater the volume of water following in a river, the larger the quantities of electric power which could be generated by the power station.

The section says that hydroelectric power generation does not produce greenhouse gases like coal power stations. In Zimbabwe, Kariba power station with an installed capacity of 1 050 MW is a typical hydropower plant with proposals for Batoka Gorge power station and small hydro power plants existing. There are two proposed power stations each of rating 1 200 MW proposed at Batoka Gorge power plant one on the Zambian side and another on the Zimbabwean side.

The section also discusses the-flow-of-river electricity generation method. The section posits that the flow-of-river schemes generates less power than hydro-dam power plants but requires less initial capital investment.

The section concludes by recommending more hydro-dam power plants for Zimbabwe especially by exploiting all dammed water used for irrigation and drinking water for cities and towns

MAIN NARRATIVE

According to Singh and Singal (2017), conventional energy sources include coal, petroleum and nuclear which pollute the environment and disturb the ecological balance. Included among non-conventional energy sources is geothermal, tidal, wave, hydro, wind and solar generation, which are abundant, non-polluting and inexhaustible in nature. The developmental trajectory in generating schemes is shifting from conventional to renewable non-conventional energy sources going forward (Singh and Singal (2017)).

Singh and Singal (2017) posits that there exist two kinds of energy sources namely renewable and non-renewable sources in the world of which hydroelectricity is renewable type. Shahgholian (2020), says that 20 % of electricity used in the global village is derived from energy sources that are renewable.

The moving waters in a river possess kinetic energy ($\frac{1}{2}mv^2$, where m =mass of flowing water=density of water x volume). According to Enbridge (2024), this energy of moving waters is exploited to produce electrical energy. U.S. Energy Information Administration eia (2024), says that the energy in moving waters is called hydropower. National Geographic Education posits that the word ‘hydro’ emanates from the Greek term with meaning ‘water’ and hydroelectricity is electric energy derived from flowing, falling or moving waters.

Hydropower is among the earliest electric energy generation sources. In hydroelectricity, a dam is normally constructed to block the water on a large river up to a certain height, that the energy in the form of kinetic possessed by moving waters is transformed into gravitational potential energy ($P=\rho qgh$, where P =Power, ρ =water density, g =force of gravity and h =head) in the extra-height or ‘head’ of the water at a higher elevation on the reservoir side compared to a lower elevation on the downstream side of the dam i.e. differences in water levels. The reservoir stores a large quantity of water blocked by the dam creating a lake. If the water at a higher elevation is allowed to fall through penstocks or large pipes inside the dam and later through turbine blades, that power which will be in the form of potential is again transformed to kinetic power in penstocks and as water strikes the turbine’s blades,

the kinetic energy possessed by water that will be falling will be transformed to mechanical rotational kinetic power of the turbine-generator set. It is the turbine's blades and in general the turbine that transforms the energy in the form of kinetic energy contained in falling waters into its own rotational kinetic energy. The turbine will be bolted or connected through a gear box to a generator.

Hydroelectricity power stations are normally situated close or on a water source such as a river, ocean or stream since its source is moving water. Flury and Frischknecht (2012) posits that constructed dams and the operation of hydroelectric power plants affect the temporal and spatial flow patterns of water and the construction consumes a lot of cement, steel, copper, gravel and energy which is used during construction.

Hydroelectricity depends on endless hydrological water-rain cycle that recharges constantly to generate electric energy.

As mentioned before, the difference in height or elevation between water in the upstream side of the dam where the reservoir is and the downstream side and the volume of water contained in the reservoir of the dam or fall is frequently referred to as the 'head'. The greater the volume of flow and the higher the head of water allowed to fall, the more hydroelectric power which can be produced from the power station. The amount of energy derived from the flowing water relies or is a function of the 'head' and volume of water. The higher the head and the greater the volume of flow, the more electricity which can be generated.

The generator operates according to Faraday principle that says when you move a magnet past a conductor, it results in electric power flowing (USGS Science for a changing world –Water Science school (2018)). In other words, if one rotates a coil of copper in a magnetic field, you produce some current in the copper coil. According to USGS Water Science School (2018), electromagnets are constructed in a generator by making direct current circulate direct current via loops of copper wire which is wound around laminations of steel arranged in stacks which are magnetic and these are termed field poles which are installed on the rotor's perimeter. The rotor is coupled or connected to the turbine's shaft and rotates at a constant speed. As the rotor spins, it causes the flow of electric current and there is the building up of a voltage at the generator's output terminals.

The civil construction which houses generators and turbines into which penstocks or large pipes feed is known as the powerhouse. Since the turbine blades centre will be connected to a rotor on the generator, that rotational mechanical kinetic energy is converted to electric power and electricity is produced. This type of electricity

generation is called ‘storage hydroelectricity’. According to Britannica (2024), hydroelectricity contributes 18 % of the global village’s total energy production capacity. According to Enbridge (2024), in 2019, hydroelectricity contributed more than 18 % of the world’s total electrical energy production.

Balmer and Spreng (2008) says that global water cycle driven by the sun provides waters in rivers and streams which become the source for renewable hydroelectricity. Hydroelectricity depends on the water cycle. The hydro-cycle or hydrological cycle is as below: -

1. The solar insolation, solar flux, solar radiation or the sun’s heat heats up water contained at the top surfaces of oceans, seas, lakes and rivers that results in water evaporating into the atmosphere.
2. Water vapor then condenses to form clouds and falls as precipitation to earth i.e. rain or snow.
3. The collection of precipitation or rainwater in rivers and streams which subsequently empty into lakes, seas and oceans where the evaporation process again takes place leading to item (1) above and hence a cycle.

Precipitation for hydroelectricity depends on the amount of precipitation or rainwater which collects into streams and rivers. According to Koch et al (2011), water resources and therefore storage hydropower is hugely impacted by water resources and the hydrological cycle.

It is to be noted that Run-of-river and tidal projects also exploit the energy of flowing or moving waters for the production of renewable electricity. There are seasonal fluctuations in rainfall and medium to long term fluctuations or alterations in rainfall patterns e.g. years of drought which significantly affect available rainwater for hydroelectricity generation.

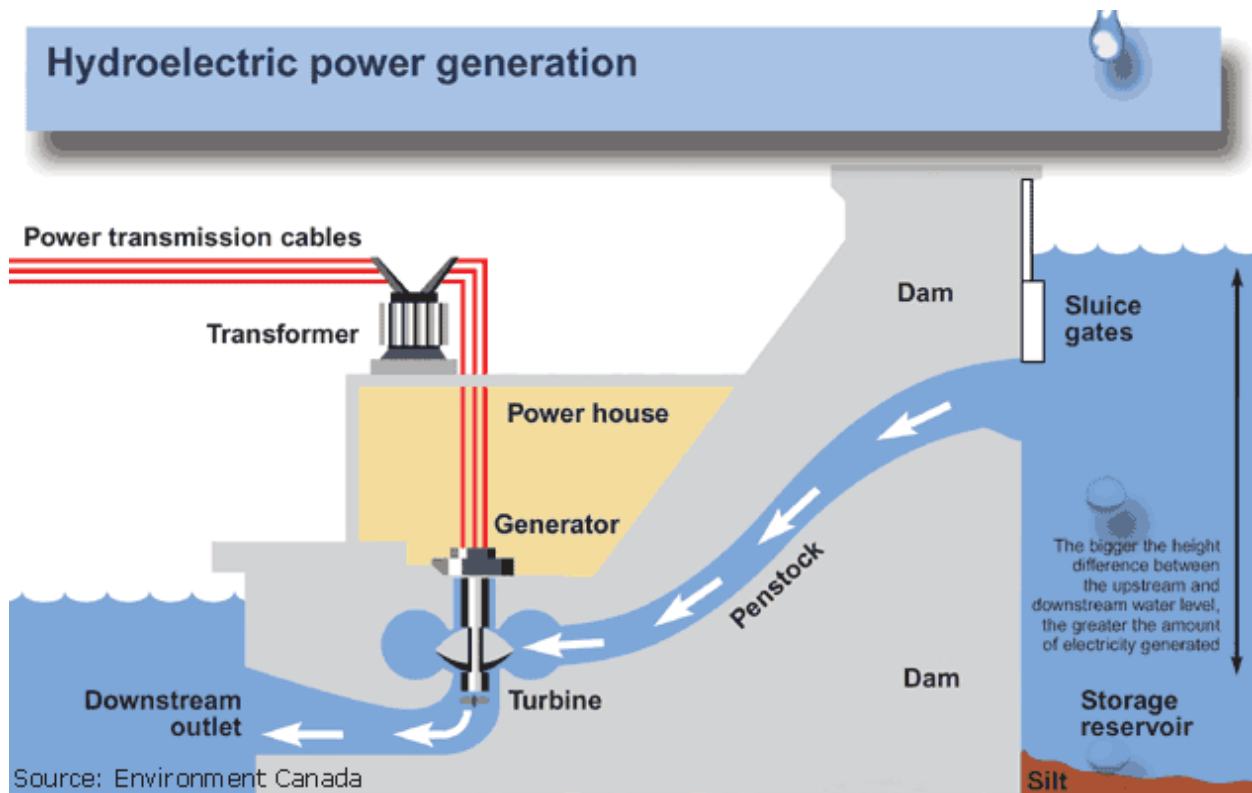


Figure 1

In the diagram above, water with a head caused by the dam wall is made to flow below sluice gates or on spillways and later via penstocks to hit turbine blades at the bottom of the dam wall causing the turbine to rotate. The turbine will be coupled to a generator which also rotates thereby generating electricity.

In storage hydroelectricity, the potential power obtained from a given volume of water is related in a direct proportion to the 'working head' (Enbridge (2024)). A high head need a smaller volume of water compared to a low head installation that generate an equal or same amount of electricity.

According to Enbridge (2024), within some dams, the powerhouse is constructed on one flank of the given dam while the other part is exploited as a spillway through which excess water is made to spill over in times of flood. Gravity causes water to fall in a penstock thereby generating electricity from falling waters in a powerhouse.

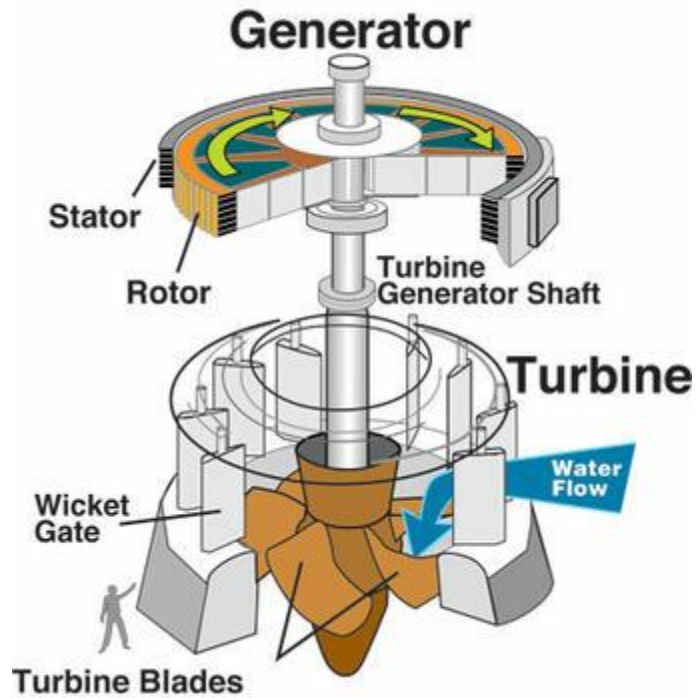
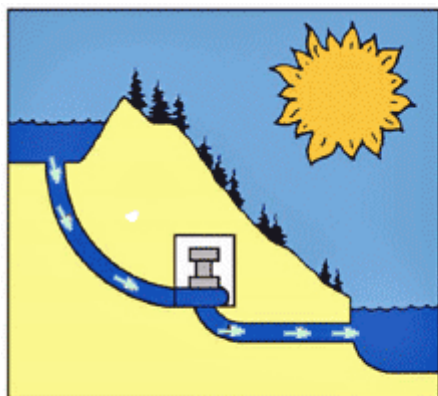


Figure 2

Above is a diagram showing a turbine coupled to a generator set via a turbine-generator shaft. The turbine-generator shaft links the turbine blades to the generator rotor which rotates as the turbine blades spin or rotate.

PUMPED STORAGE



Daytime: Water flows downhill through turbines, producing electricity



Nighttime: Water pumped uphill to reservoir for tomorrow's use

Figure 3

Electricity demand fluctuates. During the day, demand goes up and during the night demand falls. There is a morning and evening peak for domestic load. During weekdays demand is normally high and less demand occurs during weekends and National holidays. Hydroelectric power stations are considered better at efficiency at supplying peak demand within short periods of time compared to nuclear or fossil fuel electricity power stations and pumped hydro in the diagram above is one way of achieving that (Water Science School USGS (2018)). Pumped hydro reemploys the same water for more than once. The reservoir caused by Pumped hydro reservoir behaves like a battery energy storage.

In pumped hydro, water from a source of water is pumped up to a reservoir storage at a greater or higher height or elevation. Then water is pumped up to the storage when demand is low and tariffs are low and allowed to fall in penstocks to turbine blades when demand is high and tariffs are high. Pumped hydro schemes frequently consume more electric energy in order for water to be pumped to higher storage reservoirs than the electricity they generate. Pumped hydro storage power plants have a negative electric energy power production balances.

When energy demand by customer is low e.g. in the middle of the night, there is need for water to be pumped up to a storage pool that will be above the power-station. The same water is permitted to flow or fall back within penstocks and ultimately hit consecutive turbine blades causing the turbine-generator set to spin or rotate during times that demand will be high or when a big load is imposed on the grid. For meeting daily, weekly and seasonal peak loads, pumped hydro is used.

Advantages of Pumped Hydro

1. Pumped hydro storage enables generating units of hydroelectric power plants to start up rapidly and quick re-adjustments or alignment in output –i.e. flexible load-supply dispatch.
2. It's clean
3. Although the energy required to pump up water into an elevated reservoir is more than the energy produced by pumped storage, the fact that water is pumped up when electricity tariffs are low and allowed to generate electricity when tariffs are high, pumped hydro can be profitable.

HYDROLOGICAL CYCLE

The water cycle

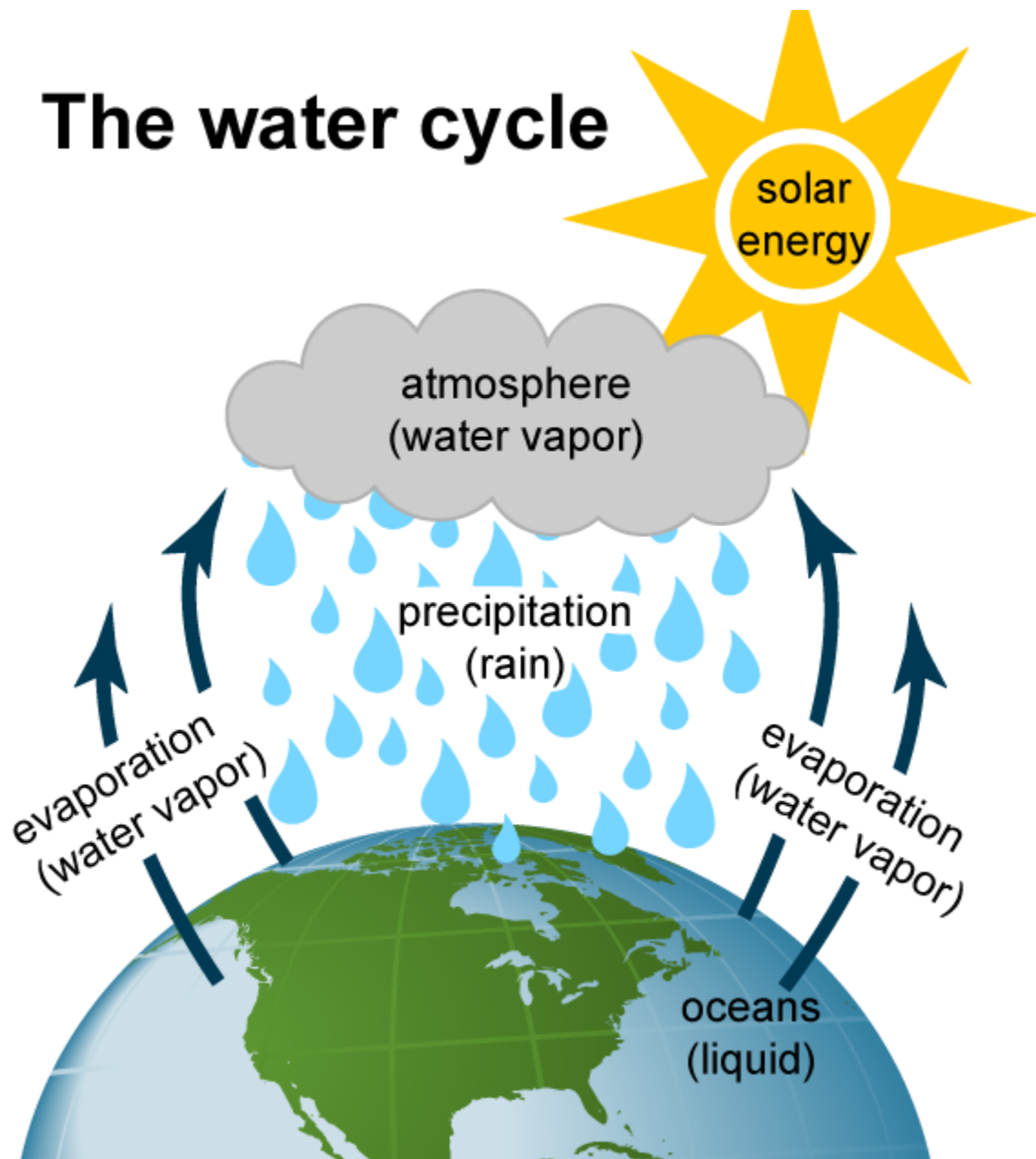


Figure 4

Above is a diagram showing the hydrological or water cycle. Water evaporates into the atmosphere from oceans, seas and rivers as a result of atmospheric temperature. In the atmosphere, the water vapor turns to clouds which at a certain level and density falls to earth as rain water which again enters rivers, lakes and oceans.



Figure 5

The diagram above shows water behind a dam wall and penstocks.

The water contained within the reservoir above possesses potential energy due to gravity that is transformed into kinetic energy as water that falls through penstocks, tunnels or large pipes. Penstocks, tunnels or large pipes are holes or channels through which water falls from the high up reservoir to the powerhouse containing turbines and generators. The structure that contains the turbines and generators is called the ‘powerhouse’ and is the place to which penstocks and large pipes feed.

To produce hydroelectricity, water in a river is controlled by damming it as shown above thereby creating a reservoir or an artificial lake like lake Kariba in Zimbabwe. Water is then guided through penstocks, large pipes or tunnels in the dam to blades of turbines. The intake system is the structure employed to regulate the flow of water. According to National Geographic Education (2024), when more electric power is needed by the grid, most of the tunnels that feed the turbines will be opened and water in the range of millions of litres will flow via the turbines and when less power is needed, the system of intake is slowed down by the closure of some of the tunnels.

A spillway assists the intake system during floods. According to National Geographic Education (2024), a spillway is a construction which permits water to flow into the river directly or other body of water below the dam thereby bypassing all tunnels, generators and turbines. The community and the dam is prevented from damage by the spillways. Spillways look similar to long ramps and are frequently dry and empty during most times.

Quick-flowing and large rivers generate larger amounts of hydroelectric power. Hydroelectric power stations close to waterfalls also produce huge amounts of energy too. A lot of energy is possessed by water crashing over the falls line e.g. Niagara Falls between U.S.A. and Canada. In Zimbabwe, the Authorities decided not to exploit that most famous Victoria Falls for power generation since it is a tourist attraction site.

Conventional Hydroelectric Plants

1. Storage dam hydroelectric power plants

In these schemes, water accumulates in reservoirs and released via turbine blades as required by demand. Kariba South Dam power plant in Zimbabwe is an example of such.

2. Run-of-the-river schemes.

In this technology, the power of the waters flowing in a large river or water currents forces the turbine to rotate. The plant has a weir in the course of the

water to channel the water to flow towards turbines. The diagram below shows run-of-the-river power plant.

According to All Programming let's talk Science (2024), run-of-river hydroelectricity gets its kinetic energy from the natural flow of a river. They don't use reservoirs and are therefore less destructive to the environment and also generate less power than storage hydroelectric power plants with reservoirs. In most cases the river flows through a turbine network system.

Run-of-River Hydropower



Figure 6

Above is a diagram showing the run-of-river scheme.

ADVANTAGES OF RUN-OF-RIVER SCHEMES

- less disruptive to rivers
- smaller effects on water flow
- no reservoirs that flood areas and displace communities

DISADVANTAGES OF RUN-OF-RIVER SCHEMES

1. run-of-river power plants do not generate much electricity
2. if the flow of the river decreases, so does electricity generated
3. prone to adverse effects of droughts

The river must be fast-flowing with enough volume of water for significant electricity to be produced by the run-of-river power stations.

TYPES OF HYDROELECTRICITY GENERATION POWER PLANTS (All Programming Let's talk Science (2024))

1. Storage Dam hydroelectricity
2. Pumped Storage hydroelectricity
3. Run-of-River schemes
4. Tidal Hydropower
5. Wave Hydropower

1 to 3 are power plants built on rivers and streams and 4 and 5 are power plants constructed in and on oceans and seas.

ADVANTAGES OF HYDROELECTRICITY

1. Hydroelectricity is a reliable, cheap, renewable and non-polluting (i.e. an electricity source that is clean) power source that does not release gases which are greenhouse into the layers of the atmosphere unlike coal generation which is dirty and releases greenhouse gases into the atmosphere. The hydrological cycle is recurrent.
2. People in nearby towns and cities can use water in the reservoir as drinking water.
3. The water in the dam's reservoir can be used for irrigation.
4. The lake created by the reservoir and its surroundings may be used for recreation, fishing, boating and water skiing by the nearby community like Lake Kariba on Kariba South Hydropower station.
5. Hydroelectricity power enables provision of affordable electricity to rural areas and is normally one of the first methods to achieve such (National Geographic Education (2024)).
6. The land surrounding these reservoirs frequently are natural places that are protected, permitting hikers together with campers to enjoy the provided natural surroundings.

7. Hydropower is a clean, reliable, renewable and hugely carbon-free (Balmer and Spreng (2008)). It has very small negative environmental and social impact compared with other electricity sources that are renewable and it is a hassle-free, efficient and clean technology (Singh and Singal (2017)).
8. It provides flexible peak load supply.
9. Hydropower is a mature, price-competitive, predictable and proven technology (Killingtvert (2014)).
10. Hydroelectricity possesses the best efficiencies of conversion compared to all other known sources of energy (approximately 90 % efficiency, water to wire (Killingtvert (2014)).
11. It needs comparatively a huge upfront investment.
12. Hydroelectricity has a long life expectancy.
13. It has a very low maintenance, overhaul and operational costs
14. Hydroelectricity possesses an energy payback ratio of between 200 and 300 that is the largest amongst all kinds of renewable energies (Killingtvert (2014))
15. It supports other variable renewables like solar and wind through offering load balancing services and storage (Killingtvert (2014)).
16. According to Balmer and Spreng (2008), it is comparatively socially and environmentally benign compared to other technologies for generating electricity.
17. Considering fuel consumption, the yearly operational cost of thermal power stations is ten to 15 times greater than that of hydro power plants.
18. No dust, smoke ash or harmful gases.
19. No nuclear and radioactive pollution.
20. Higher efficiency –hydro makes use of 80% of water resources compared to thermal power plants which reaches 30-50 % of heat efficiency (Jamil et al (2014))
21. Hydro compensate for grid instability caused by non-guaranteed sources of power that are renewable like solar and wind and –hydro plays some balancing role for the system's operations (Rubanenko et al. (2020)).
22. Hydroelectricity is the cheapest way to produce electricity today (Shahgholian (2020)).

DISADVANTAGES OF HYDROELECTRICITY

1. Certain dams can release methane which is a greenhouse gas from the decomposition of some vegetation below water (Enbridge (2024)). Rotting plants and soil under water can release toxins which accumulate in fish and birds that people eat causing diseases and illnesses in people.

2. Storage hydroelectricity systems affect water systems, constraints how water flows and therefore adversely affect animals and plants in the river. Dams interrupt the migration of some e.g. spawning fish and salmon. Dams and reservoirs prevent fish from swimming upstream. Local communities may lose wildlife and fish they depend on for food.
3. It displaces or submerges human communities and ecological sites as the reservoir fills. Communities, homes and cities may need relocation as the construction of the dam begins.
4. Exposed to water scarcity e.g. drought.
5. River banks can be flooded by Dams and destroy habitat in wetlands for thousands of organisms e.g. cranes and aquatic birds like ducks that are frequently in possible danger, including plants that rely on the habitat of the river banks that are marshy (National Geographic Education (2024)). Farming land maybe flooded.
6. Power plant operations could also raise water temperatures in the reservoir and animals and plants close to the dam might have to re-adjust to this alteration or else migrate elsewhere.
7. The building up of silt on the reservoir bed is the most limiting factor to the amount of hydroelectricity that a dam can produce. The flowing river carries the silt and the silt is prevented from arriving at normal destination in a river mouth or delta by the dam. According to National Geographic Education (2024), silt builds up to hundreds of meters on the reservoir's bottom, diminishing the amount of water in the facility and therefore less powerful energy to flow through the system's turbines. Silt buildup is avoided by a process known as siltation which requires considerable amount of money. Siltation restrict the operational lifetime of some power plants to 20 or 30 years.
8. If the dam fails downstream settlements may be in danger of drowning.

CONCLUSIONS

Hydro-electricity is a mature, clean and renewable method of generating electricity so is Central Receiver Tower (CRT) power plants except that CRT power plants are not yet mature. Both require a lot of geographical space. Zimbabwe should exploit all dammed water for electricity generation e.g. dammed water for irrigation and for drinking water for cities and towns. Victoria Falls in Zimbabwe would have been an ideal site for building a hydro-power station in Zimbabwe, but the revenue from the tourist attraction it provides becomes a discouragement for such efforts.

The project now proceeds to do a literature review and discussion of wind generation as another generation option.

2.3 Developments in Wind Energy Generation

Introduction

This section tracks developments in wind energy generation. It posits that wind is air in motion which therefore possesses kinetic energy which need to be transformed into electrical power using wind turbine-alternator sets. This section says that wind power is renewable, non-polluting, sustainable, inexhaustible and plenty energy source. The sun heats the earth-surrounding atmosphere unevenly and also at different times. This causes the heated air at certain areas to become less dense and therefore rises leaving zones of low pressure. Air from zones of elevated pressure move to areas of less pressure causing air motion which is called wind which therefore possesses kinetic energy. Whilst countries like Zimbabwe are battling electricity blackouts, they have lots of wind which can be exploited for electrical energy.

The section concludes by stating advantages and disadvantages of wind generation and proposing areas for future research.

MAIN NARRATIVE

According to Porte-Agel et al. (2019), the demand for energy worldwide continues to go up at an average of two percent every year.

Danny and O'Malley (2006) says that worldwide policy makers are encouraging and promoting renewable energy sources like wind generation because of global climate change concerns. Wind is suitable for meeting increasing power demands in most countries and minimizing fossil fuel generation which are subject to supply and price instability. According to Manwell et al. (2012), the finiteness of fossil fuel reserves and greenhouse emissions by coal generation have given rise to development of wind generation. Manwell et al. (2012) says that wind exists everywhere on the earth and has considerable energy density in some places. Previously wind has been used for transportation and mechanical power (Manwell et al. (2012).

Wind Energy Technology Office website (2024), says that wind turbines employ wind to generate electricity. Manwell et al. (2012) says that a wind turbine is a machine that transforms wind power, velocity or energy in the form of kinetic and lastly into electricity. According to Gupta (2016), wind generation is growing quickly and wind farms growing in size, magnitude and complexity. Wind is a highly variable energy source and cannot be stored (Gupta (2016)). Manwell et al. (2012) says that it is impossible to store wind for later use. The wind turbine's output is non-dispatchable and is inherently fluctuating. The best that can be done is to

constrain generation to levels less than what the wind can generate (Manwell et al. (2012). Wind is considered non-transportable and could only be transformed to electricity in places where it will be currently blowing, but wind energy or electricity it produces can be transported via copper or aluminum wires or in general by the electricity grid to which it is connected (Manwell et al. (2012) The wind turns aerodynamic turbine blades around a rotor that in turn rotates an alternator that generates electric power. According to Wind Energy Technology Office website (2024) wind energy is a type of solar energy which is as a result of three concurrent events as follows: -

1. The earth's rotation
2. The surface of the earth's irregularities
3. The heating of the earth which is surrounded by the atmosphere which is uneven

Sustainable Energy Authority Ireland website (2024), says that earth is heated unevenly by the sun and this produces thermal air currents so as to ensure attainment of equal pressure and temperatures around planet earth-giving rise to global wind. The kinetic power possessed by the wind is captured and transformed to electricity by utilizing turbine-generator sets.

According to Sustainable Energy Authority of Ireland website (2024), wind power is considered clean, inexhaustible, sustainable and renewable type of power with capacity to replace fossil fuels.

Wind-flow is modified by differences in terrain, vegetation and bodies of water. Wind creates aerodynamic force in the turbine blades. During the process that wind moves across the blades of the turbine, the pressure caused by air creates different pressures on the blade's 2 sides. Drag and lift forces are created across the blades due to differences in pressure. The drag force is less in strength than the lift which causes the rotor to rotate.

There is need to locate wind turbines in areas with a lot of wind on a regular basis. According to Menezes et al. (2018), wind varies in time and space and in addition cannot be controlled. Menezes et al. further highlights that wind turbines are subjected to transient resources, non-linear dynamics and variable mechanical loads and therefore control systems are important for wind turbines

Aims of the embedded Wind Turbine's Control Systems

- Maximization of electricity generation
- Mitigating static as well as dynamic loads of mechanical type.

- As a guarantor of continuous energy supply into the electricity grid in response to utility demands.

Menezes et al. (2018) says that the torque of the generator and pitch angle of the blade are the main parameters to be controlled in a wind turbine. According to Menezes et.al. (2018) regulation of the pitch angle permits control of the input torque of the wind, so as to facilitate generation of power smoothly and diminish the loads which are mechanical. Menezes et al. (2018) further posits that generator torque control permits changes of the speed of the wind turbine rotor soon after a Maximum Power Point Tracking (MPPT) strategy for getting as much possible power from the flux of the wind. Grid interaction control permits regulation of the quality of electricity into the grid.

3 Main Wind Turbine Control Parameters

- Control of grid integration
- Control of generator torque
- Control of the pitch

As wind velocity increases, the wind torque also enlarges and as the wind velocity decreases, the wind torque also decreases. Menezes et al. (2018), highlights the point that rotating the blades around their axis alters the relative flow of wind and as a result the aerodynamic loads imposed on the rotor.

According to Jureczko et al. (2005), so as to attain the highest possible and practical power output under specific atmospheric conditions the shape of the turbine blade is critical and the expenses of manufacturing blade of the wind turbine is approximately 15-20 % of the total production expenses of the wind turbine. One of the methods to alter stability and stiffness is to alter the shape of the blade but it could impact on the aerodynamic efficiency of the wind turbine. The other method is changing the composite material from which the blade is made from. The dynamic performance of the blade must be taken into account when blades are longer than 45m.

Gupta (2016) posits that the stochastic, intermittency, fluctuating and random nature and character of wind power that is injected into the grid results in significant changes in line power and bus voltages of the transmission system. For successful integration of wind generation, it must be free from technical abnormalities and cost effective (Gupta (2016)).

During the process that the wind hits the turbine's blades, the turbine's blades attempt to block the wind and therefore in accordance with Newton's first motion law, an equal and opposite force will emerge causing a change in momentum of the wind which also forces the blades to rotate. According to Newton's second law 'the rate of change of momentum is directly proportional to the applied force and takes place in the direction in which the force is applied. In this case the wind produces a force on the turbine blades that drives the turbine rotor. ENEL website (2024), says that the wind activates the rotor via the blades. According to ENEL website (2024), the rotors rotation is transmitted to an input shaft which powers the electric generator. This is termed the yaw system which facilitates the positioning of the nacelle depending on the direction of the wind. According to NREL website (2024), winds become more powerful and less volatile the higher up in the atmosphere the turbine blades are mounted and so turbines are placed on tall towers e.g. 30m high. ENEL website (2024) highlights that the taller the turbine-generator set, the stronger the wind because there will be few obstacles in its way e.g. buildings, vegetation and mountains. The same website says that wind turbines can be constructed in oceans, lakes or land. Land based wind energy is among the lowest cost electricity sources (NREL website (2024)).`

ENEL website (2024) posits that a wind turbine-generator set is a gadget which transforms energy in the form of kinetic energy possessed by moving wind into electrical energy. The turbine-generators set is the opposite of a fan which creates wind from electricity, while the turbine-generator set creates electrical power from moving wind. The generation of electrical power using wind is called wind power or wind generation.

According to NREL website (2024), offshore wind energy is newer and is growing. Offshore wind power can have turbine blades that are as long as a field of football. Wind energy is renewable and exploits the power of moving wind to generate electrical power. It is reliable and clean energy which is injected into the grid with no greenhouse gas emission and therefore environmentally friendly. According to Wind Energy Technology Office website (2024), the rotor is joined to the generator either via a shaft together with a series of gears (i.e. gearbox) or directly (for direct drive turbines) which increases the rate of rotation which permits the realization of a generator that is physically smaller. The transformation of aerodynamic force into spinning of a turbine-generator set produces electrical energy.

Wind Energy Technology Office website (2024), says that there exist two kinds of wind turbines which are (1) horizontal-axis wind turbine (HAWT) and (2) vertical-

axis wind turbines (VAWT). Schubel and Crossley (2012) says that a turbine which possesses a shaft installed horizontally parallel with respect to the ground is called a horizontal axis wind turbine (HAWT) and if the shaft is normal with respect to the ground it is termed a vertical axis wind turbine (VAWT). According to Manwell et al. (2012), Horizontal axis wind turbines(HAWT) have the axis of rotation that is parallel to the ground. Wind turbines can be constructed on offshore (on water e.g. lakes, seas and oceans) and on land. Horizontal axis turbines are the commonest and most efficient kind of wind turbines (ENEL website (2024)) and dominate the market. The VAWT was discontinued because of low tip speed ratio and difficulties in regulating the speed of the rotor. Hardships in starting vertical axis turbines have further hindered development. HAWT possess 3 blades with the blades facing the wind which is called upwind. The generator is located at the top of the turbine. Vertical axis turbines are rare relatively as they have less efficiency in terms of air resistance. The generator in vertical axis turbines is located at the base of the turbine.

Manwell et al. (2012) highlights the fact that Horizontal Axis Wind Turbines (HAWT) are normally categorized pivoted on the orientation of the rotor (downwind or upwind of the tower), control of rotor (stall or pitch), design of hub (teetering or rigid), number of blades (2 or 3 blades) and how aligned they are with respect to the wind (active yaw or free yaw). Most turbines nowadays possess upwind rotors and 3 blades. According to ENEL website (2024), 3 blade horizontal axis wind turbines are better and balanced more. It is impossible for wind turbine efficiency to exceed 59.3 % according to Schubel and Crossley (2012).

If P =Power

ρ =air density

A =area of swept

V =velocity of wind

Wind therefore carries the power $P=1/2\rho Av^3$

According to Schubel and Crossley (2012), the relationship existing among the variables (a) rotor velocity and (b) wind relative velocity is called '**tip speed ratio**'

If τ =tip speed ratio
 Ψ =speed of rotational (rad/s)
 r =rotor radius
 v_w = speed of wind

$$\tau = \frac{\Psi r}{v_w}$$

Higher tip speeds are associated with an enlargement of aerodynamic and centrifugal forces. According to Schubel and Crossley (2012), modern HAWT normally use a tip speed of 9 or 10 for motors with two blades on the rotor and 6 to 9 for 3 bladed rotors. The reduction in kinetic energy of moving air caused by the blades of the turbine translates to kinetic energy of rotation of the turbine-generator set. According to Schubel and Crossley (2012), the force of aerodynamic is the integrated impacts of the skin friction and pressure which is driven by or results from the flow of air over the aerofoil's surface. Schubel and Crossley (2012) posits that the angle between the angle of incidence of the wind and the blade is called as the angle of attack (α)

There are wind fields grid-connected and distributed wind schemes. According to Office of Energy Efficiency and Renewable Energy website (2024), distributed wind power are energy projects which serves onsite demand for energy e.g. a home, farm, school or business. Wind is air in motion and the turbine-generator set converts wind air's energy in the form of kinetic to electricity. The wind's energy in the form of kinetic is transformed to mechanical kinetic energy of rotation of the turbine generator set by turbine blades and the kinetic energy of rotation of the turbine-generator set is in turn converted to electricity using the generator.

Research with design, falling costs and supportive policies have driven the quick growth of wind energy since the year 2000. Enhanced technological breakthroughs have witnessed the falling down of costs and increased capacity factors.

The quantities of power that could be exploited from moving wind rests on and is a function of the turbine's size and blade length.

Output  (dimensions of rotor, cube of wind speed)

According to Energy Education website (2024), blade radius, wind speed and air density influence and affects power output.

According to Manwell et.al. (2012), most turbine blades are manufactured with composites of mainly fiberglass and plastics that are reinforced with carbon fiber, although at times from laminates of wood/epoxy.

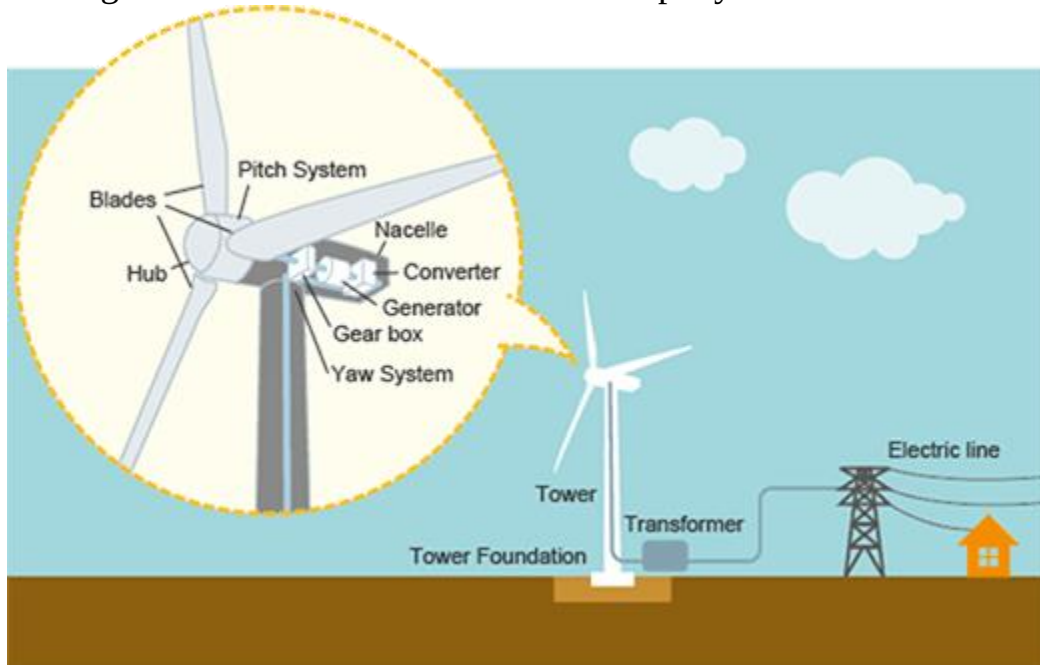


Figure 7

Above is a diagram showing how wind turbine blades are rotated by wind and through a gearbox system rotates the generator rotor thereby generating electricity.

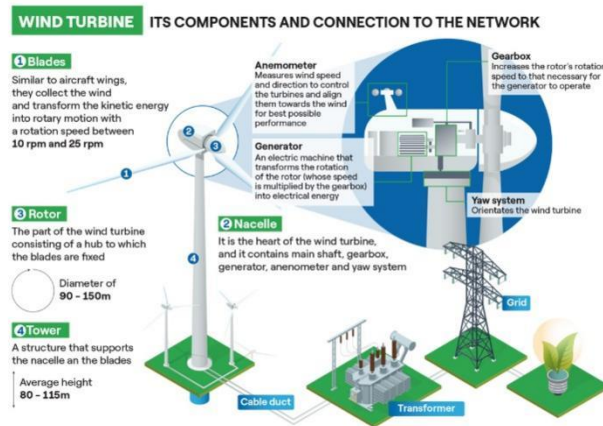


Figure 8

Major Components on a Turbine that Employs Wind To Generate Electricity

Major parts on a turbine that uses wind are as follows according to ENEL website (2024): -

1. Foundation
2. The tower with cables to transformer
3. The nacelle (gearbox and generator)
4. The rotor and hub
5. The turbine blades- with average length of 52 m.

According to Manwell et al. (2012), the major parts constituting a horizontal axis wind turbine are the following: -

- The rotor comprising of the supporting hub blades that are frequently considered the most crucial parts on a turbine from (a) the overall cost and (b) performance.
- The gear drive train that comprises the parts that rotate on the turbine excluding the rotor. This includes the generator, mechanical brakes, coupling, gearbox and shafts.
- The nacelle which include the yaw system and the wind turbine housing, main frame and bedplate.
- The foundation and the tower
- Controls of the machine
- The balance of transformers, switchgear, cables and possibly power converters that are electronic.

Drive Train

According to Manwell et al. (2012), the drive train include gearbox, shaft that is high speed and shaft that is low speed. Other parts comprise rotating parts of the generator, 1 or more couplings, brake and the support bearing. The function of the gearbox is to increase the speed of the rotor's rate of rotation from a low level value (tens of rpm) to an appropriate rate for driving a standard generator in the range of hundreds or thousands of rpms. (Manwell et al. (2012)). Parallel shaft and planetary gearbox are 2 kinds of gearboxes employed in wind turbines according to Manwell et al (2012).

Generator

Turbines that use wind employ induction or synchronous generators. Many turbines operated and coupled to grid-connected applications employ squirrel cage induction generators (Manwell et al. (2012)). Major advantages of this kind of generators which are induction fed are that it is inexpensive, simple to connect to an electricity grid and rugged. The generator which is doubly induction fed is increasingly becoming a popular option today (Manwell et al. (2012)).

Nacelle and Yaw System

According to Manwell et al. (2012), this encompasses the housing of the wind turbine, the bedplate of the machine, the yaw orientation system and the Main frame. Manwell et.al. (2012) says that the main frame offers the means for the proper alignment and mounting of the parts of the drive train. Manwell et al. (2012) further posits that the cover of the nacelle protects items inside from the weather effects. According to Manwell et al. (2012), an orientation yaw system is needed to ensure and maintain proper alignment of the rotor shaft in relation to the wind and its vital part being a big bearing which joins the tower to the main frame.

Tower and Foundation

According to Manwell et al. (2012), the supporting foundation and the tower itself is critical for the proper functioning of the wind turbine. The main kinds of tower design now in operation are the type that are free-standing employing concrete towers, lattice (or truss) towers and steel tubes. The height of the tower is normally 1 to 1.5 times the diameter of the rotor but in always normally 20m (Manwell et al. (2012)).

Downwind turbines are normally noisier than the upwind turbines (Manwell et al. (2012)).

Controls

These include actuators, power amplifiers, controllers, sensors and intelligence.

Balance of Electricity System

These encompass pitch motors, power factor correction capacitors, transformers, switchgear, cables and power electronic converters.

Manwell et al. (2012), posits that the major items to consider in wind turbine construction and design encompass: -

1. Blade Numbers (2 or 3)
2. Rotor orientation (downwind or upwind of tower)
3. Material of blade –profile and method of construction
4. Design of hub-teetering, hinged or rigid
5. Control of power through stall control (aerodynamic regulation) or pitch blades that are variable (control of pitch)
6. Changeable or fixed motor speed
7. Free yaw orientation (action of self-alignment) or active yaw (control which is direct)
8. Generator of the Induction type (doubly fed or squirrel cage) or Synchronous
9. Gearbox or Direct drive generator

ENEL website (2024) says that the nacelle has to be oriented depending on the wind direction. At speeds of wind greater than 10 km/h the rotor begins to work and at wind speed above 90 km/h, the turbine shuts down. Turbines which use wind are normally anywhere in the range 80 meters and 115 meters high and turbine blades are between 10m and 85 m long. ENEL website (2024) posits that on average 200 tons is the weight of a turbine which uses wind. The average electrical energy of a wind turbine is 2-3 MW. The materials used in constructing the tower of wind turbines are steel, resin, fiber glass, plastic, iron, cast iron, aluminum, copper and wood.

Strbac et al. (2007) says that wind generation has higher investment costs than conventional gas or coal but wind generation saves fuel and decreases operation costs. Wind is normally variable and difficult to predict. According to Strbac et al. (2007), the normal utilization factor for wind generation is about 35 %. The intermittency of wind generation compels the retention of conventional plant to guarantee security of supply. Wind therefore may not provide the needed dynamic voltage and frequency control. According to Strbac et al. (2007), the installed generation capacity need to be greater than peak demand for wind generation because of variability of the wind resource.

A conglomerate of multi-generation units is called wind farms. The pioneering wind turbine was invented in 1887 by James Blyth.



Figure 9

The above picture shows a wind-field for wind generation. The wind generators on different towers may be connected in series to increase the voltage output or in parallel to increase the current output. According to Manwell et al. (2012), there was a shift to the development of offshore wind power, a reduction in wind turbine manufacture and large megawatt-sized wind turbines in the 1990s.

Wind energy generation happened in the United States and United Kingdom in 1885 and 1887 respectively according to IRENA International Renewable Energy Agency website (2024). As of 2020, Denmark was the global village leader in the exploitation of wind power followed by Ireland according to Sustainable Energy Authority of Ireland website (2024). EMBER website (2024) says that wind power produced 7.8 % of the world's electricity during the year 2015 thereby doubling its share from the year 2015 where it had 3.5 percent of the world-wide's total generation. Gupta (2016) says that renewable worldwide generation capacity as of

2013 reached about 1 560 GW with wind contributing 318 GW. According to Menezes et al. (2018), the world wind installed capacity by 2015 was 370 GW.

Advantages of Wind Generation (Toshiba Global website (2024))

1. No CO₂ emissions.
2. Minimal impact to the environment's air and water
3. Exists everywhere
4. Safe energy source
5. Easy generation
6. Simple equipment
7. Few effects to natural environment. It doesn't pollute.

Wind energy contributed 7.33 % of worldwide electricity generation in the year 2022 according to ENEL website (2024). Gupta (2016) says that offshore wind farms with planned capacities in excess of 1 000 MW are being planned.

According to Dicorato et al. (2011), in offshore wind farms, wind turbines have larger diameters and rated power than those employed in onshore applications as the strong wind conditions enables better exploitation of the wind resources.

Disadvantages of Wind Energy

1. Land use and property value effects
2. Health and safety to wildlife e.g. birds can be killed by rotating blades
3. Interference with radar

Areas for Future Research

There is need for research on materials that make wind turbine longer, lighter, more durable and better at generating energy in order to reduce costs (NREL website (2024))

The thesis now proceeds to do a literature review on Thermal and Solar Generation.

2.2.0 LITERATURE REVIEW ON THERMAL AND SOLAR GENERATION

Garg and Prakash (2000) emphasizes that all substances or materials whether they be solid, liquid or gaseous emit and release energy in the form of electromagnetic waves at temperatures higher than absolute zero. This kind of energy is termed radiation. Radiation is thought to transmit energy in small packets called ‘photons.’ Garg and Prakash (2000) posits that radiation the emitted from sun is the most important to human race. The radiation of practical usefulness to solar energy users lies between 0.15 and 3.0 μm . Garg and Prakash (2000) says that the sun is a ball or sphere of fire consisting of hot gaseous matter with a diameter of $1.39 \times 10^9\text{m}$.

Garg and Prakash (2000) highlights that the sun with its constituent gases is a continuous fusion reactor as the ‘containing vessel’ retained by the forces of gravity. Hydrogen atoms fuse to form one helium atom with loss of mass $E=mc^2$. Some of the mass having been converted to light and heat energy.

The earth rotates one rotation about its axis every 24 hours contributing to day and night experiences and complete a revolution about the sun in a period of roughly 365.25 days contributing to seasons of the year. These dynamics causes fluctuation of solar radiation at any point on earth.

Garg and Prakash (2000) posits that the sun subtends an angle of 32° on earth.

Sunlight, solar radiation or solar flux is radiated from the sun which is $1.5 \times 10^{11}\text{m}$ away from the earth (Garg and Prakash, 2000). This sunlight can be converted to electricity using various means.

According to Freris and Infield (2009), there are two main technologies for the conversion of sunlight into electricity namely: -

(a) Photovoltaic(PV) and

(b) Solar thermal system (Concentrated solar power(CSP) plants).

Freris and Infield (2009) posits that **Photovoltaic(PV)** directly convert solar flux into electricity. Efficiencies of solar panels range from 12% to 18 % although experimental panels have achieved 30% efficiencies.

Solar thermal systems in contrast depend on indirect conversion of solar radiation via heat to electricity.

According to Freris and Infield (2009), 'Fossil fuels have one thing in common, they all create carbon dioxide when burnt. They constitute a crucial component of the long term earth's carbon cycle. Climate alteration is driven towards unwanted direction by the unlocking of the stored carbon e.g. increased temperatures globally.

Kotler (2002:56) posits that the best assurance of the allegiance of customers, the only path to sustained average growth and earnings and the most powerful defense against foreign competition is quality. This demands high obsession with quality and high intimacy in this thesis. -quality of power station in design, installation, operation and maintenance of concentrated solar power plants and when integrated and retrofitted in coal power stations is our concern.

Many authors have emphasized the advantages of Renewables. Quality refers to needed frequency, needed voltage levels, absence of voltage dips, voltage flicker and harmonics. There must be zero negative impacts on environment and people. The thesis tries to design a 500 MW power tower power plant.

It is in this endeavor that solar energy is founding its superior place in power industries worldwide. The over dependency on non-renewables like coal has led to risks of exhaustion of these depletable resources.

Concentrated Solar Power

Concentrating solar energy plants employ many large mirror surfaces to concentrate and focus sunlight onto a far smaller area of the absorber where it is transformed into thermal energy at temperatures of about 565 °C. This heat is used to raise the temperatures of the Heat Transfer Fluid (HTF) e.g. sodium nitrate and potassium nitrate. The HTF via a heat exchanger raises the temperature of water so that it becomes steam and then subsequently produce high pressure that drives the power block which is also known as the heat engine (i.e. turbine-generator set) that produce electric energy in a fashion friendly to the environment.

According to Kuravi et al. (2012), says that CSP plants have a big advantage in that they can be coupled to energy storage systems and can also alternatively jointly operate with coal and gas in order to mitigate the intermittency of solar radiation. By furthering the time of usage of the heat engine beyond sun hours, the levelized cost of electricity is reduced for the plant

According to Blanco and Santigosa (2017), 'There are 4 main technologies to collect and concentrate the direct solar radiation into a receiver (a) 2 Line focus concentrators and (b) 2-point focus concentrators

Line Focus Concentrators

(a)parabolic troughs and

(b)linear Fresnel

Point Focus Concentrators

(a)parabolic dishes and

(b)central receiver systems are also known as solar power towers. This being the power plant that is the central focus of the design for the thesis i.e. a 500 MW power tower or Central Receiver Tower Power Plant.

According to Blanco and Santigosa (2017), the following depicts currently existing plants

Power plant Type	% of total in existence
Parabolic trough	90%
Linear Fresnel	5 %
Central Receiver Tower	5%

TABLE 6

Blanco and Santigosa posits that mirrors are important in the collection and concentration of solar insolation as they are the first component in the plant and in the energy transformation process. The heliostats are the most expensive in terms of

initial investment costs and during operations and maintenance of the plant. Solar mirrors are also known as reflectors.

COAL POWER STATION

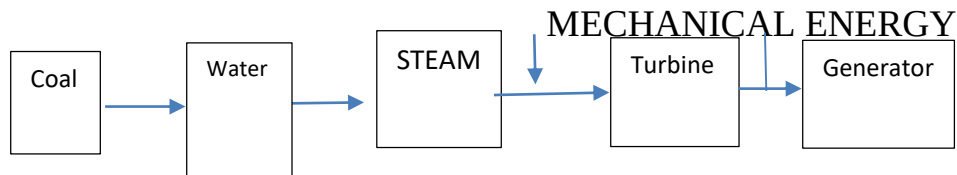


Figure 10

In coal power plants, one ignites coal that raises the temperature of water that is transformed into superheated steam. The steam which is superheated is directed via nozzles to produce pressure employed to give mechanical energy required to drive the turbine-generator set thereby producing electricity. The steam under pressure hits the turbine blades producing rotational kinetic energy that makes the generator rotates within a magnetic field thereby producing electric energy. In the proposed Central Receiver Tower Power Plant, one replaces coal heating with Solar Thermal heating.

The energy conversion efficiency at each stage is very important in the design and therefore construction of a solar thermal power station

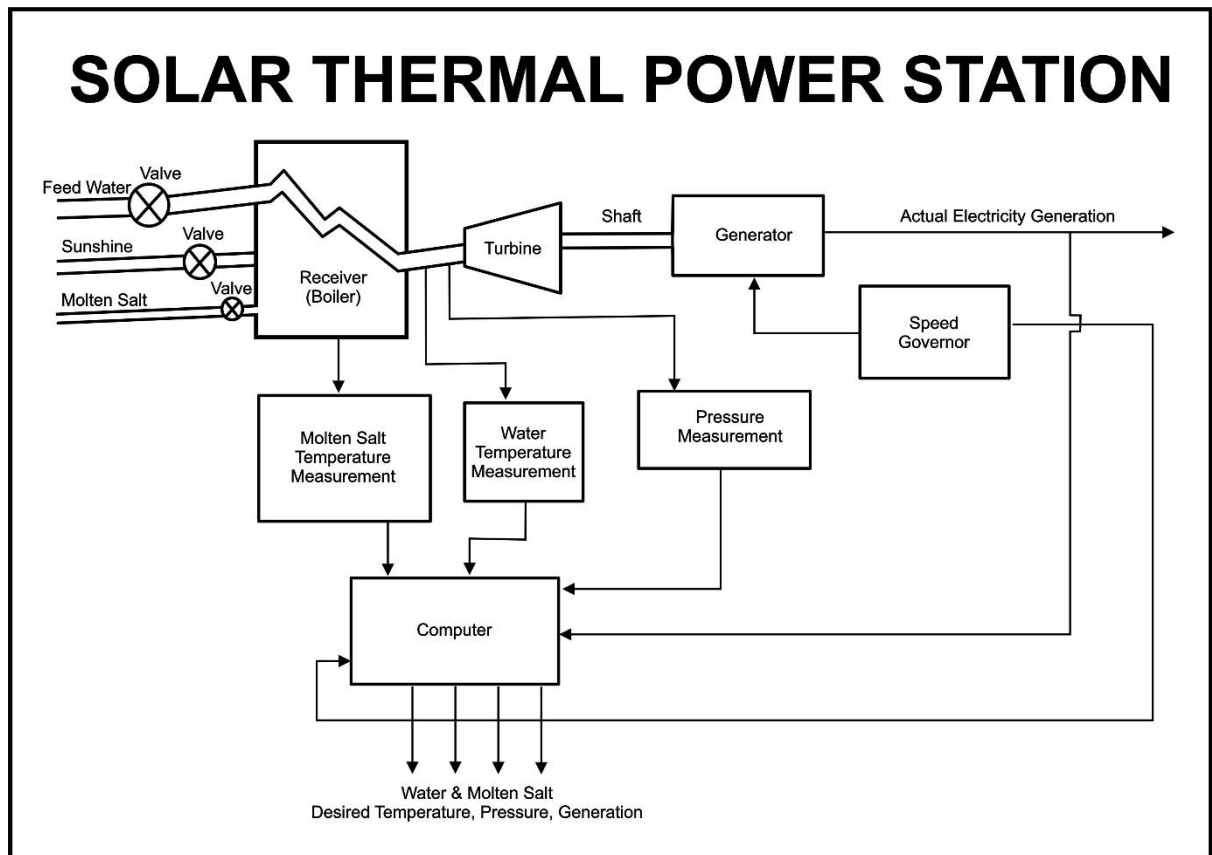


Figure 11

Figure 11 shows how electricity is generated in an automated concentrated solar generation plant.

We need to measure (a) output electrical power from the generator using CTs, VTs and electricity meters to control everything except frequency which should always be 60 Hertz

(b) rotational speed of the turbine using a tachometer which should be 60 turns per second

© steam pressure

(d) temperature in energy storage tanks and receiver using pyrometers

For feedback control purposes

According to Blanco and Santigosa (2017), 'The main aim or goal of a control system for power tower solar field or heliostat field is to keep the temperature at the outlet of the field near to a desired set point by controlling the total surface area of the mirror array/heliostat exposed to or trapping the sun energy for concentrating onto a receiver in the design and installation stage of the project and also by the solar tracking system.

Solar energy which is the primary source of energy, is difficult to manipulate. The Heat Transfer Fluid or molten salt flow is employed as a regulating signal. The set-point could be altered significantly throughout the operations dynamics of the day as a result of changes in the generating needs, seasonality fluctuations and sun's insolation conditions. A flow-meter is needed within the tubes to the turbine and in-between the thermal energy storage tanks and receiver in order to produce the control signal.

The delay in transport is powerfully dependent on the regulating signal (i.e. the flow of molten salt). The control of the solar power station becomes trickier at low flow. Dead time compensator is crucial as the solution to this problem.

.

Overall energy stored in Thermal Energy Storage systems = $mc\Theta$ where m = mass of the Heat Transfer Fluid (HTF),

c = specific heat capacity of HTF Θ = Temperature of molten salt in hot storage tank above atmospheric temperature

Thermodynamic considerations of exergy, entropy and enthalpy being taken into considerations.

2.2.1 Advances in Thermoelectric Generation

INTRODUCTION

This research section reviews literature on thermoelectric generation which is generation of electricity based on the thermocouple principle and the Seebeck effect. It highlights constraints currently facing thermoelectric generation such as little power output yield as a result of low efficiencies. The conflict need of requiring high Seebeck effect, high electrical conductivity and low thermal conductivity has resulted in low efficiencies of thermoelectric gadgets in the past. Various thermoelectric materials are discussed particularly semi-conductors.

The section highlights that the very low efficiency of thermoelectric devices has resulted in limited commercial application. The section further highlights that due to discoveries and improvements in thermoelectric materials in the second half of the twentieth century, efficiencies have been enhanced such that thermoelectric devices are now competitive with certain conventional generator devices. The advantages of thermoelectric generation are proffered

The section is concluded by recommending areas for future investigation and research.

MAIN NARRATIVE

Problem Statement

Climate change considerations, sustainability, depletion of fossil fuels, environmental friendliness and safety issues have compelled modern engineers to try to abandon fossil fuels and also consider and desire to improve efficiencies of generation processes. Renewables which are clean and environmentally friendly in place of fossil fuel generation also need to replace fossil fuels. If fossil fuel generating plants are closed without alternatives, the world may be thrown into

darkness. In addition, the efficiencies of certain heat processes are not ideal and needs improvement.

The world is confronted with an ever increasing demand for energy because of rising population and economic development. Thus there is a twin need for new power generation plants as well as need for the efficient use of energy inclusive of electricity. There are many methods of generating electricity inclusive of hydro, fossil (e.g. coal and oil thermal), nuclear, tidal, wave, geothermal, Concentrated Solar Power(CSP), piezoelectric, thermionic, hydro, wind and thermoelectric generation.

Among the renewables currently considered include wind energy, central Receiver Tower Power plants, photovoltaics, parabolic trough, Linear Fresnel, parabolic dish, hydro and thermoelectric generation. Tidal and wave generation are other forms of renewable energy sources. There is world pressure through the United Nations COP meetings to scale down on coal generation and hence there is need for substitutes such as thermoelectricity which is a clean source of energy that increases efficiency in the utilization of energy i.e. increases capacity to exploit waste thermal energy. According to Villa (2022), many countries signed the Paris agreement which committed them to reduce global warming which need energy efficiency and increased use of Renewables. As mentioned in the abstract, low efficiencies have previously prevented wide deployment of thermoelectric generators and coolers.

According to Tan et al. (2019) attention has been drawn to thermoelectric materials in the past two decades with the desire to harvest waste heat and transform it to electricity. The idea was to improve the thermoelectric material's efficiency as specified by a figure of merit that is dimensionless.

A thermoelectric generator according to Harpster et al. (2024) is a solid state machine that converts heat into electricity directly or transform electricity into thermal cooling or thermal heat. Thermoelectric generators can be used together with solar panels.

According to He et al. (2014) environmental degradation and energy shortage crisis are current problems currently confronting the world. Global warming, climate change, ozone layer depletion, greenhouse gas emissions and acid rain are current barriers to sustainable wide use of fossil fuels. He et al. (2014) posits that thermoelectric generation is proposed as one possible way among others, of mitigating environmental damage. It is a clean way of generating electricity and effecting refrigeration with no moving parts, scalable, with long life span and minimal operation and maintenance requirements. Da Rosa (2019) says that a thermoelectric generator can produce electricity directly as a heat engine since if there is a temperature gradient or difference across it, it can generate a voltage. A Thermoelectric generator (TEG) is a heat engine where the working fluid is replaced by charge carriers. The Carnot efficiency limits its efficiency. Da Rosa (2019) is convinced that thermocouples have efficiencies which are substantially less than thermomechanical engines.

Villa (2022) says that it is estimated that in developing countries about 30% of energy is wasted. In countries like Turkey about 51 % of industrial energy is lost unexploited. There is need to trap, utilize and exploit such wasted energy in industrial processes, power generation and automotive industry in order to further enhance efficiency. This is where thermoelectricity comes in.

Methodology

When two ends of an electrical thermocouple have different temperatures an electrical voltage is established in the thermocouple. Thomas Johann Seebeck was the first to describe this phenomenon and hence the name Seebeck effect.

Seebeck coefficient= electrical voltage established/temperature difference.

According to da Rosa (2009), the absolute Seebeck coefficient of a normal conductor is the coefficient of the material working against a superconductor. Lead's Seebeck coefficient was established to be between 7.2 and 18K. Below 7.2K lead becomes a superconductor. The effect disappears above 18K.

SEMICONDUCTORS' SEEBECK COEFFICIENTS

All metals have a Seebeck coefficient smaller than 100 microvolts/K. Some semiconductors have Seebeck coefficient of about 300 microvolts/K at usable temperatures. This means semiconductors have figures of merit advantage over metals and hence have found a bigger place in thermoelectric generators. According to da Rosa (2009), the semiconductors' Seebeck coefficient depends on the doping level. Whether the semiconductor is of p-type or n-type determines the polarity of the Seebeck effect. Intrinsic semiconductors have zero Seebeck coefficients.

The figure of merit (ZT) is dimensionless. Each semiconductor has a range of temperature over which its ZT is best. Da Rosa (2009) says that for low temperatures around 100 °C, Bi_2Te_3 is normally employed. At higher temperatures around 500 °C, PbTe was normally used. Nowadays tellurium-antimony-germanium-silver is now the most used. For very high operational temperatures SiGe alloy is used. Da Rosa (2009) posits that doping PbTe with sodium results in a p-type semiconductor and an n-type results from doping PbTe with lead iodide. Both polarity is required by a thermocouple.

Thermoelectric materials having acceptable performance include bismuth antimony tellurium alloy. In the 1990s the idea of employing skutterudides was launched. Skutterudide is the generic name for cobalt and nickel ore found near Skuterud in Norway. Venkatasubramanian et al (2001) reported a p-type $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ super lattice device with a $\text{ZT}=2.4$ at room temperature.

The reverse whereby a voltage difference produces a temperature difference is called the Peltier effect. The Peltier effect is used for heating or cooling in nanotechnology and microelectronics.

The two dissimilar conductors in a thermocouple are thermally in parallel and electrically in series.

Making thermoelectric materials with better performance involves varying three physical parameters (a) thermal conductivity (b) Seebeck coefficient and (c) electrical conductivity. According to Elsheikh et al. (2013), heat from human bodies, motor vehicles, computers, factories and power plants can be converted to electricity using thermoelectric energy converters.

Elsheikh et al. (2013) posits that the advantages of thermoelectric devices are as follows: -

- solid state operation
- vast scalability
- absence of toxic residues
- no moving parts and no chemical reactions
- maintenance-free operations
- a long operational life expectancy
- simplicity
- no vibration and therefore no noise pollution

Making a current flow through the junction of two dissimilar conductors or semiconductors can cause them to behave as a cooler or heater. This means according to Villa (2022), thermoelectric devices can operate in two different modes i.e. thermoelectric cooling and also as thermoelectric generator- that is as in refrigeration and power generation modes.

There is need to consider thermoelectric modules as comprising of a P-N junction connected thermally in parallel and electrically in series.

Uchda et al. (2008) defines Seebeck effect as the generation of electric voltage by putting a conductor in a temperature gradient.

Elsheikh et al. (2013) also says that solid state thermoelectric devices can also alter electricity into thermal energy for heating and cooling employing the Peltier effect which is the reverse of the Seebeck effect. The efficiency of thermoelectric(TE) devices cannot compete with traditional refrigeration and power generation technologies.

Flipse et al. (2012) defines the Peltier coefficient as the term which describes the amount of heat that is carried by an electrical current when it passes through a material.

Seebeck effect

Temperature gradient → electricity

Peltier Effect

Electricity → temperature gradient

He et al (2014) says that heat is emitted from vehicles, many industries, electrical instruments, fossil and solar thermal power stations. Such heat may be utilized in thermoelectric generation. Thermoelectricity is reversible meaning you can convert heat to electricity and convert electricity to heat. He et al (2014). is convinced that thermoelectric devices are currently in limited operation because of low energy harvesting efficiency and high cost of thermoelectric materials.

He et al. (2014) alleges that the discovery of semi-conductor materials has greatly assisted in the development of thermoelectric devices. Thermoelectric generation is dependent on the Seebeck effect principle.

MATERIALS FOR THERMOELECTRIC GENERATION

Among some of the materials identified to-date for thermoelectric generation includes semi-conductors, polymers and ceramics. Examples of polymers include ethylenedioxythiophene, carbon fibre polymer-matrix structural composites. Bismuth Telluride and its alloys are also thermoelectric material employed mainly in refrigeration and electricity generation at moderate temperatures. The Seebeck and Peltier effect appears in thermocouples rather than in single materials. Best materials for generation are also best materials for refrigeration at any given temperature.

The three semiconductors having low thermal conductivity and a high power factor are (a) bismuth telluride (b) lead telluride (c) silicon germanium. Thermoelectric materials can be classified as new materials and conventional materials. New materials include tetrahedrites, skutterudites and rattling ions crystals.

Sharma et al. (2017) says that thermoelectric materials has three classes depending on the range of temperature of application: -

- (1) low temperature range ($< 177^{\circ}\text{C}$) Bi based alloys
- (2) Medium temperature range (177°C to 577°C) Pb alloys
- (3) High temperature range ($> 1027^{\circ}\text{C}$) Si –Ce based alloys

Low Temperature Materials(300-500K)

According to Tan et al. (2019) Bi_2Te_3 and its alloys have ZT values of around 0.9 - 1.0 around room temperature. Tan et al (2019) posits that they are mainly used for cooling applications. Soldering, welding technology and fabrication flexibility of Bi_2Te_3 thermoelectric devices have given focus recently. Tan et al. (2019) says that nanosizing was applied during the 2000s and this marginally increased its ZT value to just over 1. Melt-spinning and ball rolling techniques were employed to form nanostructuring inside the bulk materials in the late 2000s. The nanosized grains were effective in scattering thermal energy carrying acoustic phonons and reducing thermal conductivity. Zhao group did hot deformation which lowered thermal conductivity of Bi_2Te_3 materials. Band structure engineering was used to enhance ZT values. Sn formed resonant impurities in the valence band of the Bi_2Te_3 . The resulting resonant scattering enhanced the Seebeck coefficient. The ZT values of p and n type Bi_2Te_3 was found to be approximately 1.5 and 1.2 at 400 K. A record ZT value of 1.86 was reported in p-type Bi_2Te_3 at 320 K in 2015 by Kim et al (2015). The question of scaling up from laboratory to industry is still open.

MgAgSb was synthesized by hot pressing technology combined with ball milling. The low sound velocity and complex crystal structure of MgAgSb contribute to low thermal conductivity. It possesses a high valence band degeneracy of 8. A peak ZT of 1.2-1.4 at 500K was reported with p-type conduction. An 8.5 % conduction efficiency under a temperature difference of 225K was demonstrated.

MID-TEMPERATURE MATERIALS(500-900K)

Lead chalcogenides, PbTe has ZT surpassing 2 for p-type PbTe . PbSe or PbS have low thermal conductivities. PbSe achieved a peak ZT value of about 1.54 at 773K. Approximately ZT value of 1.7 at 900K was reported for p-type PbSe and have higher melting point. The other material is skutterudites known as CoSb_3 .

HIGH TEMPERATURE MATERIALS (GREATER THAN 900K)

SiGe alloys are used. The n-type SiGe shows a ZT value of 1.1 at 1200K. Half-Heusler (HH) alloys are another group of high temperature materials.

The doping of Sb at Sn sites fine tune the carrier density to optimal levels. The disadvantage is high thermal conductivity and effort to decrease it has been made.

Ball-milling nanostructuring like in PbTe was used to decrease thermal conductivity.

Thermoelectric materials like Bi, Sb and Te are highly expensive, toxic and unstable at high temperatures and therefore safety precautions have to be taken when using them.

Polymers are cheaper, have light weight, are flexible and abundant.

According to Goldsmid (2014)

$$Z = \alpha^2 \sigma / \eta$$

Where α = Seebeck coefficient

σ = electrical conductivity

η = thermal conductivity

There is need to maximize Z for each branch of the thermocouple.

According to website:- https://en.wikipedia.org/wiki/Thermoelectric_effect

If the two ends of dissimilar metals or semiconductors joined together at one junction are subjected to different temperatures, a voltage is generated (thermocouple principle) between the other ends not joined together. This realization is now being used to generate electricity-thermoelectric generation or thermoelectricity.

Since the receiver in CST power plants present temperature differentials between the receiver or thermal energy storage tanks and the atmosphere, it would be prudent to also incorporate thermoelectric generators with the junction of two metals or semiconductors at the receiver or energy storage tanks and the other ends at atmospheric temperature!

This is generation of electricity from the principles of a thermocouple where if there is a temperature difference at a junction of two metals or thermoelectric materials, a voltage will be established at the two ends of such materials-the hot end and the cold end.

Thermoelectricity is electricity that is obtained from the direct transformation of temperature gradient or difference to electricity through the thermocouple principle. When a temperature difference exists at the junction of two metals or semiconductors, a voltage is created. When a voltage is applied to the thermocouple, there is transfer of heat from one side to another thereby making available a temperature difference.

A temperature difference causes charge carriers contained in the material to move from the hot side towards the cold side. The thermocouple principle can be used to generate electricity or to measure temperature using pyrometers in very hot regions like furnaces, solar absorbers or thermal energy storage tanks in Central Receiver Tower power plants. Temperature controllers can be effected by thermoelectric devices.

The thermoelectric effect comprises of the following three effects (a) the Thomson effect (b) the Peltier effect and the (c) Seebeck effect.

According to website: <https://www.intechopen.com/chapters/65239>

According to Enescu (2019), the ambient energy sources used for energy harvesting are temperature gradient, electromagnetic radiation, light, motion and chemical energy (Figure 1).

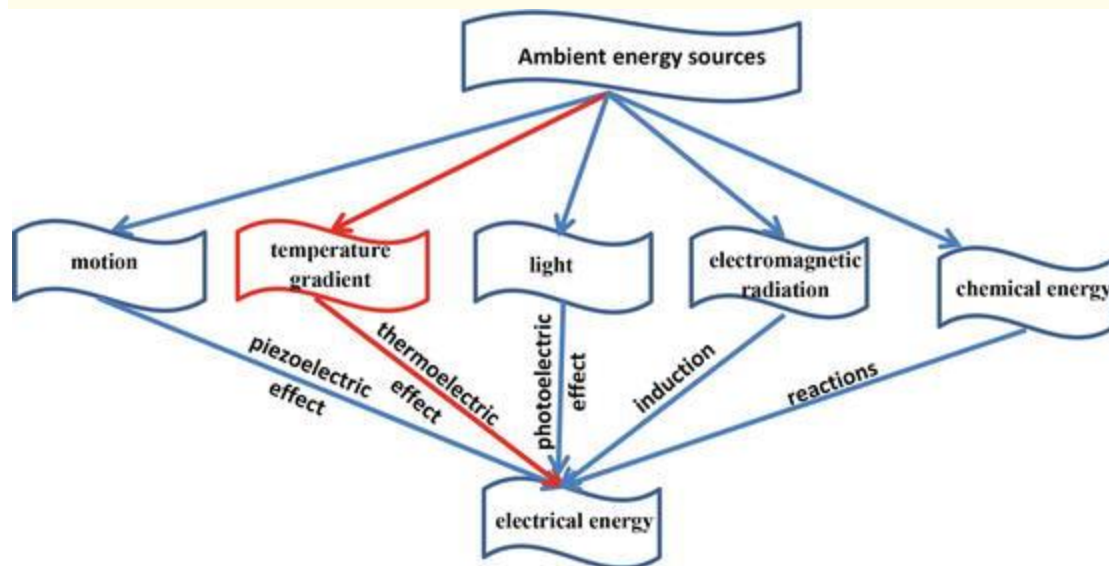


Figure 12

The above figure shows how ambient energy sources are converted to electricity using various means

Anescu (2019) posits that extensively exploited energy harvesters are: radio frequency harvesters that depend on the trapping of the radiation of the ambient radio frequency, piezoelectric harvesters that depend on human motion or mechanical vibrations (that transform stress or pressure into electrical energy), chemical

harvesters which depend on different reactions on the surfaces of electrodes, electromagnetic harvester that depend on induction, light harvester that depend on the photoelectric effect and the thermal harvester that depend on the thermoelectric effect

Anescu (2019) says that thermoelectric energy harvesting mainly depends on the operation of the thermoelectric generator (TEG). Anescu (2019) posits that a TEG converts heat directly into electrical energy according to the Seebeck effect. Anescu (2019) says that in this case, the motion of charge carriers (electrons and holes) leads to a temperature difference across this device. In addition, energy harvesting schemes using thermoelectric can produce power ranging from hundreds of microwatts (Mw) to milliwatts (Mw) for different transmitters and sensors.

According to Anescu (2019) unlike thermodynamic PV systems or conventional heat engines (Rankine, Stirling), the energy conversion efficiency of the TEG is limited to about 5–15%.

A solar absorber is the receiver in Concentrated Solar Power (CSP). Thermoelectric generators can be implemented complementary with CSPs.

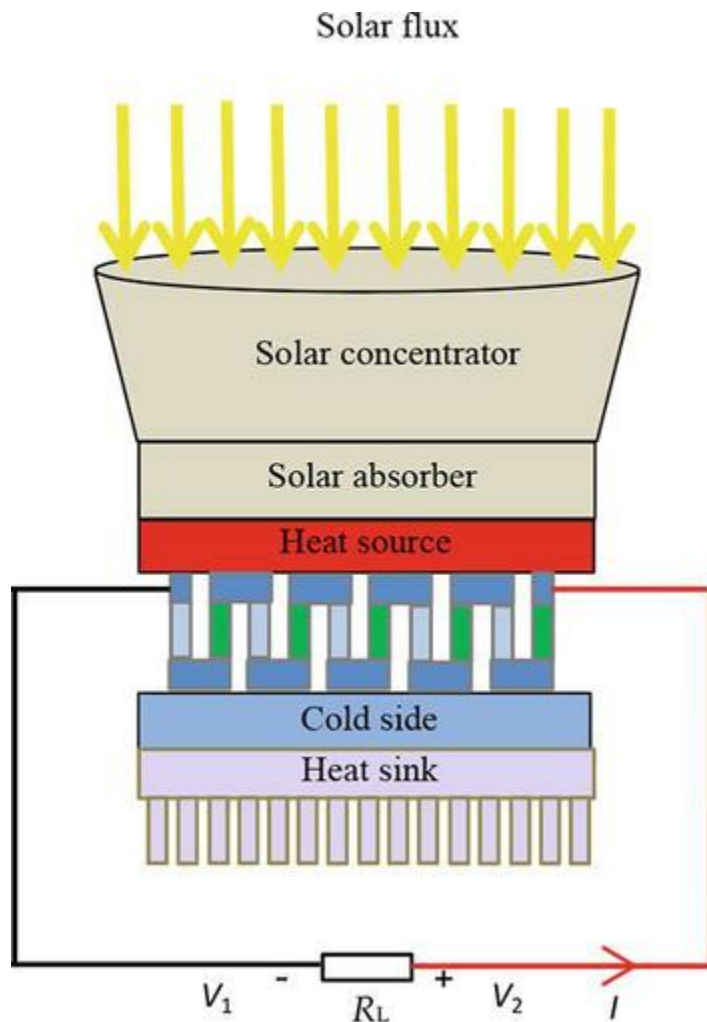


Figure 13

The above diagram shows how sunlight is concentrated and heats a solar absorber which becomes a heat source for thermos-coupling with a cold side.

According to Rosa (2009), 'thermocouples find use as (a)thermometers (b)generators capable of transforming heat directly into electricity and (c)heat pumps and refrigerators.

The liked temperature range principally determines the choice of the thermocouple.

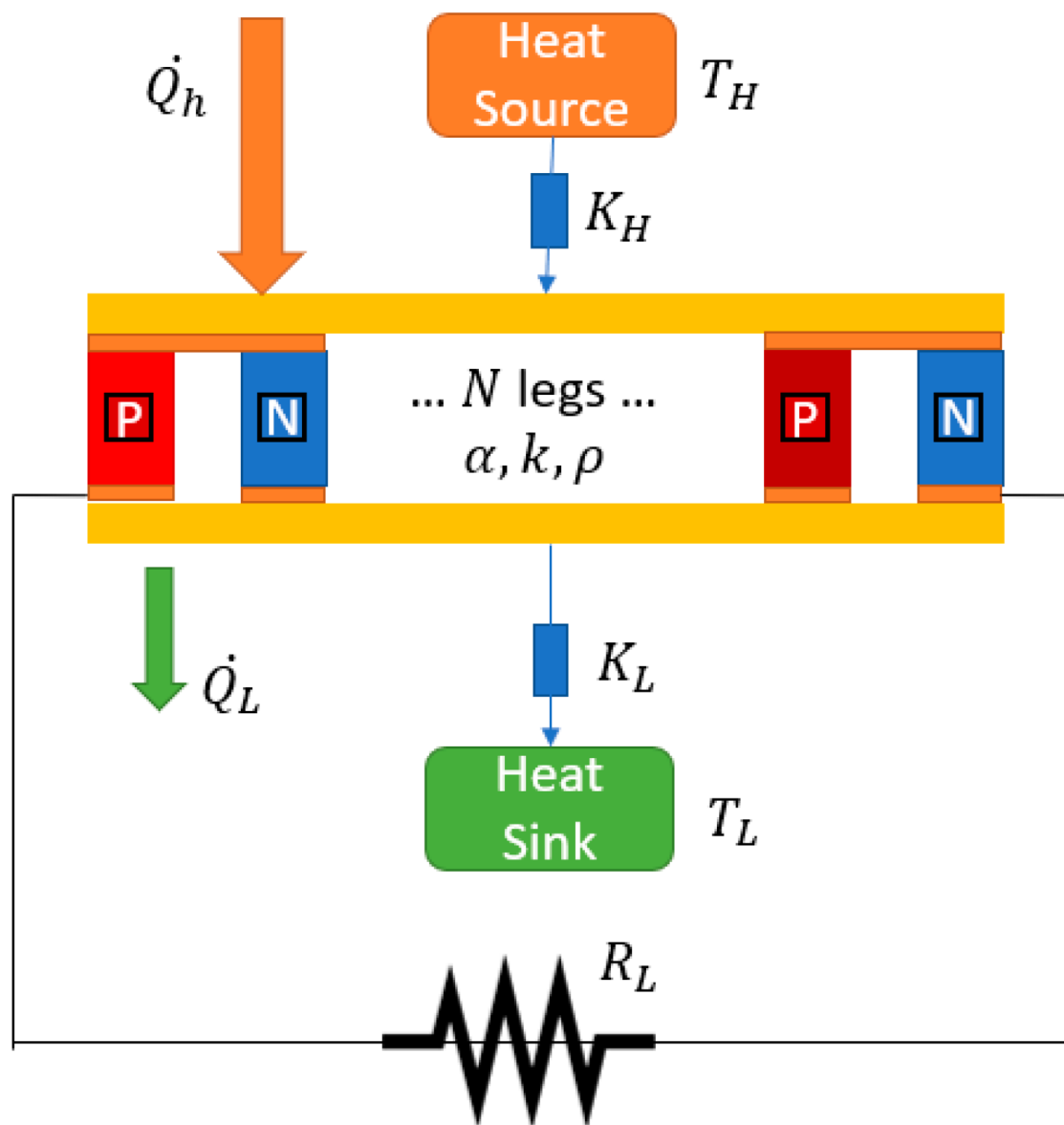


Figure 14

p-n junctions are electrically in series and thermally in parallel.

The Thermoelectric Generator

According to Rosa (2009), 'The capacity of a thermocouple to produce a voltage when there exists a difference in temperature across it implies that it can be exploited as a heat engine with ability to generate electrical power directly. Thermoelectric generators are also referred to as Peltier or Seebeck generators. They are ideal for off-grid remote locations that have a heat source. Examples of heat sources are fireplaces, exhaust pipes, woodstoves, furnaces, diesel and gasoline engines, boilers and solar concentrators.

The Carnot efficiency limits the heat engine's efficiency

According to Goldsmid (2020), the coefficient of performance and efficiency of a thermoelectric generator of a thermoelectric heat pump are related to the cold and hot junction temperature and a quantity known as the Figure of Merit (ZT).

Goldsmid (2020) posits that

$$ZT = ((\alpha_p - \alpha_n)^2 T) / \{ (\kappa_p / \sigma_p)^{1/2} + (\kappa_n / \sigma_n)^{1/2} \}^2$$

Where

α = Seebeck coefficient

σ = electrical conductivity

κ = thermal conductivity

According to Goldsmid (2020), we assume that the difference in thermal levels between the junctions is much smaller than the absolute temperature, T.

As a generator, the efficiency is: -

$$\eta = \left(\frac{\Delta T}{T} \right) \times \frac{(M-1)}{(M+1)}$$

$$\text{where } M = (1 + ZT)^{1/2}$$

The figure of merit for single material $ZT = (\alpha^2 \sigma T) / \rho k$.

Snyder and Snyder (2017) says that the Figure of Merit is a variable that is useful for comparing and evaluating different thermoelectric materials.

$$ZT = S^2 T / \rho k$$

Where S=Seebeck coefficient

T=absolute temperature

k=thermal conductivity

ρ =electrical resistivity

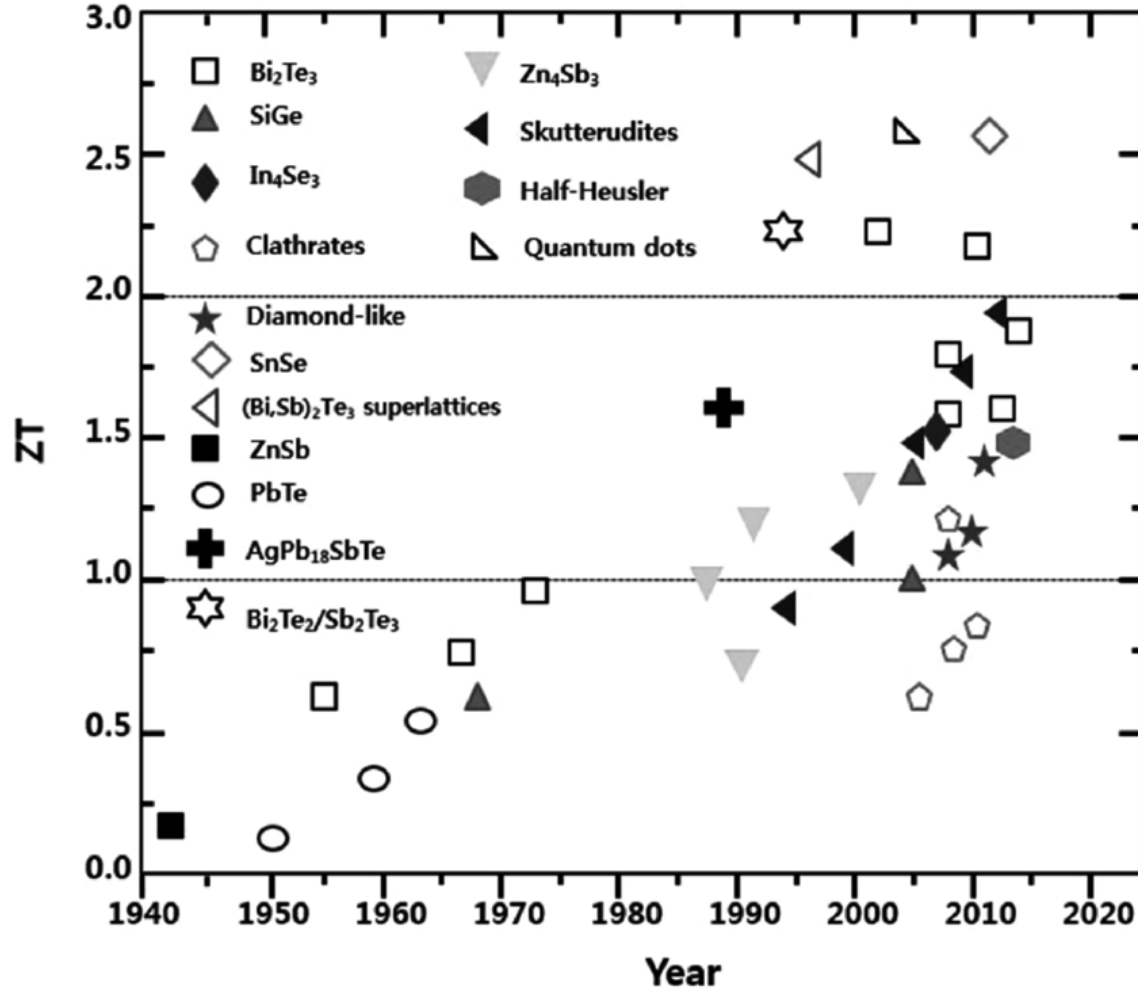


Fig 15: A number of thermoelectric materials and their Figure of Merit

A high figure of merit is desirable for thermoelectric generators.

A figure of merit is employed in determining the efficiency of thermoelectric generators and thermocouples. Sharma et al. (2017) posits that a figure of merit measures the conversion efficiency. According to Sharma et al (2017), by controlling materials electronic structure, lattice vibrations and charge carrier concentration the figure of merit can be improved.

Goldsmid (2020) says that there have been significant improvements in the thermoelectric materials in the second half of the twentieth century and it's now possible to manufacture thermoelectric generators that can compete with conventional devices. $ZT=4$ has been achieved facilitating widespread application of thermoelectric technology.

Typically, the efficiency of thermoelectric generators is around 5 to 8 %. With ZT values of 3 to 4 efficiencies can be enhanced to 33-37% permitting thermoelectric generators to compete favorably with certain other heat engine efficiencies.

The Physics Of Thermoelectricity

According to da Rosa (2009), four different mechanisms are at play in the analysis of thermocouples namely heat conduction, Joule losses, Seebeck effect, Peltier effect and Thomson effect.

Heat Conduction

Motion of carriers and crystalline lattice's vibration conducts heat. Reduction in performance of thermocouple is experienced due to heat conduction.

Joule Losses

Joule losses are the result of lattice imperfections' scattering of carriers. As current flows through the thermoelectric generator or thermocouple, it encounters resistance resulting in generated heat.

The Seebeck Effect

A voltage develops as a result of temperature difference across a thermocouple. The increased concentration of carrier in the cold region of the conductor creates this voltage. A thermocouple must invariably comprise of two dissimilar materials frequently of opposing polarity.

The Peltier Effect

When carriers leave one medium and enters another different medium, there is a change in heat capacity of carriers which causes the junction of dissimilar materials to release or absorb heat.

Thomson Effect

The flux of drifting carriers convert heat.

PRACTICAL LIMITATIONS

- Low efficiency
- High electrical output resistance creating self-heating problems
- Low thermal resistance (heat from digital microprocessors cannot be removed fast enough.)

APPLICATIONS

Thermoelectric technologies have applications in aerospace, military, scientific laboratory, industrial consumer, medical, transportation and power generation. As research continues more areas of applications will evolve. The highest figure of merit obtained experimentally using thermoelectric materials $ZT=4$. Higher figures are unlikely in the near future. Thermoelectric generators (TEGs) can be integrated into existing systems to boost efficiency and usage of waste energy. TEGs produce d.c. and inverters are required for a.c. and this lowers the efficiency and adds to complexity and cost.

According to da Rosa (2009) thermoelectric generators have found application where unattended operational activities is more important than efficiency for example: -

1. Stationary power plants' cycles topping
2. Spacecraft's power supplies operating at a big distance from the sun which takes advantage of photovoltaics.
3. As generators for installations where oil is produced including ocean platforms
4. Air circulating fans' electric power suppliers incapable of operating during power failure.
5. Auto motive's power supplies taking advantage of the engine's heat
6. Providing energy needed to open the main valve of the gas heating system.
7. In submarines

Sources of heat for thermoelectric generators include: -

- Reject heat from exhaust gases from automobiles making the overall efficiency more.
- Burning fuel
- Radioactive decay

Conclusion

When a temperature difference is applied across a thermocouple, a voltage is established across it. This effect is called Seebeck effect which has given rise to thermoelectric generation. Thermoelectricity is electricity generation using the thermocouple and Seebeck effect. The Peltier effect is the reverse of the Seebeck effect and is mainly used in thermo-coolers and refrigeration. Semimetals, semiconductors and polymers are some of the thermoelectric materials exploited in utilization of waste heat. Thermoelectric generation exploits waste heat from human beings, motor vehicles, industries and power generation. The low efficiency in thermoelectric devices has previously hindered the widespread application of thermoelectric generation. However, during the second half of the twentieth century

breakthroughs have been achieved in terms of efficiency such that currently thermoelectric devices are becoming competitive in certain areas with conventional generation devices. Thermoelectric generation is a clean, sustainable and environmentally friendly generation method. Areas where thermoelectric generation have recently experienced success are in the areas of portable power production and waste heat recovery. Future research will continue to be on increasing the figure of merit for thermoelectric materials, Thermoelectric generators have found application in aerospace, military, scientific laboratories, industrial consumer, medical, transportation and power generation.

The project now proceeds to discuss photovoltaic as a source of electricity supply.

2.2.2 Photovoltaic(PV) Solar Fields-Grid Connected

INTRODUCTION

Modernization is a metric measure of advancement, recency, newness and progress made in terms of enriching the prosperity levels of a nation or human race in terms of economy, finance, materialism, social and psychological! Scientific ideological thrust and bias has since time immemorial been the fuel powering modernization in terms of living standards of the human race. It has also determined the rate, pace, level and trajectory of modernization.

The modernization revolution started with industrial revolution. Then came the electronic communication revolution and now the solar clean energy revolution.

Modernization is a positive transformation from a backward, primitive and archaic society to a sophisticated, fashionable and luxurious world.

Solar energy is now a new vehicle for achieving modernization in terms of energy sources and protecting our environment from adverse climate change and pollution. A new tool for achieving modernization.

In recent times we have seen purely electric cars which uses solar panels, batteries and electric motors to drive motor vehicle wheels. This is modernization as opposed to purely gasoline, diesel and petrol cars in older times. Rooftop solar solutions, solar fields or solar power stations grid connected has also modernized power generation methods

Climatic change considerations and other adverse effects on human beings, flora and fauna caused by fossil fuels and advances in renewables have fashionized green generation methods like Solar Photovoltaic(PV) which can be implemented as rooftop solutions, ground-mounted, wall-mounted, floating or solar fields grid-connected. This paper investigates critical issues and considerations in solar photovoltaics. The paper highlights also that solar cells are manufactured from silicon material that in turn is manufactured in high temperature furnaces from sand. These photovoltaic solar cells directly convert solar insolation or irradiance directly into electricity unlike the Concentrated solar thermal power plants which first

convert sunlight to heat and thermal energy into electric energy via a power block or heat engines.

The paper highlights that energy storage schemes like battery banks, together with regulators, inverters and single phase-to-three-phase-converters are required for installation purposes. The paper concludes by alleging that wide deployment of solar fields grid connected is inevitable and certain given COP26 & COP 27 United Nations meetings which is putting pressure on member countries to adopt electricity green energy generation methodologies. These solar fields grid connected can be coupled to Concentrated Solar Power Stations(CSP) to give hybrid generation units. The section also concludes that as research in solar generation methods intensify, the installation, operation and maintenance costs for same will plummet as manufacturers and power utilities goes past the learning curve in terms of executing their mandate.

METHODOLOGY

Research can be categorized into two main classes namely non-experimental and experimental. This research adopted the non-experimental archival research. Internet, google scholar, dimension and Scopus journals on photovoltaics were consulted and findings reported in this section. Textbooks on solar energy were also consulted as part of the research.

MAIN NARRATIVE

Rising energy demand, climate change considerations and depletion of the traditional fossil fuels have caused the world to witness a surge in interest in renewables of which photovoltaic(PV) generation is one. PV therefore partly helps meet growing world energy demand and avert climate change, environmental issues and problem of depletion of fossil fuels. According to Chaur et al. (2011), Renewable energies are energy sources which get replenished at the same rate as they are used. Chaur et al. (2011) further says that Photovoltaics(PV) are friendly environmentally, do not pollute the atmosphere, are easy to install, simple to design and has low maintenance costs. They have no moving parts, no noise and no environmentally damaging by-products. According to Green (2002) Photovoltaic is an adjective that

describes the production of electricity as a result of sunlight energy falling onto a solar cell. Boyle (2012), says that photovoltaic is the direct conversion of solar rays or solar flux into electricity in a solid state device. Nelson (2011) says that on totally cloud days' power is about 10 % of that on sunny day with clear sky. During a cloudy day most sunlight flux is diffuse whereas on a sunny day most of the sun's rays are direct. According to P. Moore (2008), 'The earth is a planet whilst the Sun is a star. All the stars seen and visible on any night without clouds are suns with a certain number of them more luminous, hotter and larger than our sun. They appear so much smaller and dimmer only because they are so much further away.' The sun is the source of solar energy. According to M.A. El-Sharkawi (2009: p71), 'The sun is the origin of all of the renewable energies with the exception of geothermal and tidal energy.' These resources (hydrogen and geothermal, tide and wave, solar, wind and hydropower) release less pollution compared to the burning fossil fuels and are renewable and are constantly replenished.

Solar insolation has the problem that it is highly variable, intermittent, stochastic and random.

If there is solar generation variability and there is no energy storage or compensatory generation done by the other power stations, supply will be reduced at night, in cloudy conditions and also rainy conditions etc. This may include inefficient use of the grid/network and may necessitate load-shedding which will become an impact of integrating solar generation onto the electricity grid in increasing quantities. Hundred percent (100%) grid supply with solar will definitely magnify the above problem. The impact of a wholly solar (100%) supplied grid without energy storage system can be felt in a solar grid-independent installation. Such grid isolated (grid independent) solar installations with batteries can help appreciate the effects of energy storage systems on the quality of supply.

Chaar et al. (2011) says that the history of Photovoltaics (P.V.) started in 1839 when physicist Alexandre-Edmund Becquerel noticed that chemical reactions were induced by certain light which resulted in electrical currents.

Nelson (2011) posits that the United States and Japan led in the installation of photovoltaics in the 1990s and then Germany exceeded Japan in 2005. Spain assumed

number two in 2008. According to Nelson (2011) installations are now mainly grid connected: residential, industrial and utility in the United States. During the 1990s, Europe, Japan and the United States were the main manufacturers of P.V. cells and modules. According to Nelson (2011), the tigers of Asia have up-scaled production and in 2000 China led the world with about 2.39 GW of production. According to Professor of Renewables G. Boyle (2012: p 98), Arrays of PV may be added to the roofs of existing buildings/houses, normally by mounting them on rails on top of the roof. According to the same author, in the roofs of new dwellings they can in some circumstances replace all or part of the conventional roof. The power utility meters have to be bi-directional to enable tariff 'credits' as well as 'debits' depending on whether the consumers are supplying to the grid or drawing supply from the grid.

A decade later, effects which were similar were seen in solid selenium by scientists. In 1900 the manufacture of the initial solid state device emerged and made way for the initial silicon solar cells to be made with about 6 % efficiency. According to Bagnall and Boreland (2008), currently photovoltaic production is based on silicon wafers which are reliable and durable with 20 % efficiency. Cheap semi-conductor thin films are an alternative. PVs are increasing in importance and constitute a billion-dollar industry. Photovoltaics do not need a heat engine like in concentrated solar power technologies. Boyle (2012) alleges that silicon is the second most abundant element in the earth's crust. According to Boyle (2012) PV has no moving parts and therefore theoretically there is no wear and tear and its output is electricity which is the most useful form of energy, According to Garg and Prakash (2000), silicon is the major material for making solar cells with other materials being Cds(Cadmium Sulphide), GaAs (gallium Arsenide). Garg and Prakash (2000) posits that silicon cells present an efficiency of 26 % and attempts are being made to lower the cost of silicon solar cells.

Materials are grouped into 3 classes namely (1) conductors (2) semi-conductors and (3) insulators. Within conductors, the electrons in the outer shell are free to move and are not bound to specific site thereby readily conducting electricity (Garg and Prakash, 2000). According to Garg and Prakash (2000), metals are conductors having conductivity of the order of 10^6 mho/cm.

Within insulators, the outer shell of the atom has 6 or 7 electrons and hence as a result the electrons are tightly bound and are unable to convey electric current (Garg and Prakash, 2000). Insulators have conductivities in the order of 10^{-10} mho/cm.

Semiconductors lie between these 2 extremes above. The atoms of semiconductors could have 3, 4 or 5 electrons in the outer shell and these electrons could be freed only if some additional energy is supplied (Garg and Prakash, 2000). Semiconductors slightly conduct electric current. According to Garg and Prakash (2000), the conductivity of semiconductors can be altered by orders of magnitude and quantity by introducing new foreign elements called dopants e.g. phosphorus and boron. It is possible to change the conductivity of silicon from 0.001 to 1000 mho/cm by the addition of dopants. Both electrons and holes are responsible for carrying current in semiconductors. Silicon possesses 4 valence electrons and phosphorus has 5 valence electrons and if we mix the 2 we get n-type. Boron has 3 valence electrons.

Garg and Prakash (2000) says that atoms and molecules are the fundamental units on which the study of chemistry is based.

According to Green (2002), up to 1940, the photovoltaic gadget with the highest efficiency were either Se, CuO or Ti_2S as the layer that absorbs sunlight and rectifying metal contact.

Goetzberger et al. (2003) says that solar cells are arranged in modules containing a layer of thin film material that is connected internally in series or a number of silicon cells connected in series.

Modules are formed from the combination of solar cells and they have an output of from 10 to 300 W according to Nelson (2011).

Silicon Crystalline Structure

Crystalline structure silicon makes solar cells. These solar cells are combined to form P.V. modules or solar panels. Connecting solar panels in series results in constant current whilst the voltage increases. While connecting solar panels in

parallel results in constant voltage and increased current. There is constant research and development to improve efficiency and its capability. There is monocrystalline, polycrystalline and emitter wrap which all fall under crystalline structures. According to Chaar et al. (2011), in crystalline solar cells, pieces of semiconductor are sandwiched in between glass panels to make up modules. Polman et al. (2016) posits that monocrystalline silicon cells have approached near complete light trapping, carrier collection and are mainly constrained by remaining carrier recombination losses. According to Polman et al. (2016), polycrystalline CdTe thin films have 21.5 % efficiency and offer good light absorption but possess high recombination losses. Goetzberger et al. (2003), posits that crystalline silicon in its monocrystalline and multi-crystalline form currently dominate the PV market. Nelson (2011) says that single crystal has most expensive production method. The single crystal has average module efficiencies of 10-12 % and is reliable.

Thin Film Technology

There is potential of making less the cost of P.V. by diminishing manufacturing and material cost while maintaining lifespan without being hazardous to the environment. Chaar et al. (2011) says that thin film panels are made by depositing a thin layer of certain material onto stainless steel substrates or glass. Nelson (2011) says that because of boundaries between crystals, polycrystalline thin films have less efficiencies. Nelson (2011) highlights that thin films are made by deposition as thin ribbon.

Polman et al. (2016) posits that thin film single crystalline GaAs cells have 28.8 % efficiency and exhibit minimal recombination losses and can be enhanced by better light management.

According to Polman et al. (2016), perovskite cells have 21% efficiency and Cu (In, Ge) (Se.S)₂(CIGS) cells have 21.7 % efficiency and possess bad light management, but CIGS exhibit higher electrical qualities. Goetzberger et al (2013), highlights that thin film crystalline silicon is currently under Research and Development.

Higher efficiency greater than 20% materials have application in utility power generation.

Compound Semiconductor

In this arrangement, complex crystalline layers stack having band gaps which are different are tailored to absorb a lot of the solar flux. Chaar et al (2011) posits that compound semiconductor cells are more robust during exposure to outer space radiation.

Nanotechnology for PV Cell Production

Introduction of nanoscale parts reduce limitations observed in other PV technologies by the capability to regulate the energy band gap providing interchangeability and flexibility and also enhance the chances of charge recombination.

Nelson (2011) says that semi-crystals' production costs are lower and efficiencies are lower with module efficiencies of about 10-11 % and however cell performances may degrade with time.

Nelson (2011) posits that amorphous material is vaporized and deposited on stainless steel or glass and has lower production costs and module efficiencies are 7-8 % and it degrades over time.

Applications of Photovoltaics according to Parida et al. (2011) are as follows: -

- Reverse osmosis plants
- Space vehicles and satellite
- Communications
- Megawatt power stations
- Rooftop solutions –solar home
- Remote building
- Pumping of water
- Source of power

Nelson (2011) says that applications of PV are as follows: -

- Grid connected
- Village power-hybrid with other energy sources like wind

- Standalone lights, radio, T.V., water pumping, water purification, water desalination
- P.V. for schools, clinics and local government offices

Demand for photovoltaics is therefore increasing every year.

Purpose of Module according to Goetzberger et al. (2003) are: -

- Protecting solar cells against ambient
- Gives a higher voltage compared to that of a single cell that produces less than 1V of voltage

According to Nelson (2011), the thin films and amorphous are cut to panel size and a typical module or panel consists of the following: -

- top surface which is transparent that is normally glass
- encapsulate normally ethyl vinyl acetate thin sheets that bind together the rear surface, solar cells, and the top surface.
- sheet of thin polymer and rear layer typically Tedlar for sealing the module
- frame which is normally aluminum
- electric connections

Nelson (2011), says that a report of cell efficiencies of about 40 % have been ventilated for multi-junction semiconductors in the laboratory.

The fundamental building block used to build PV system is the solar cell. According to Nelson (2011), individual cells can vary from 1 to 10 cm. About 1.2 W that is not sufficient to energize numerous applications is produced by one cell. Nelson (2011) highlights that therefore cells are combined to form modules and modules into solar panels, panels into arrays for utility large scale power applications. Nelson (2011) posits that thin-film materials for example cadmium telluride and amorphous silicon can be made directly into modules. Nowadays, PV gadgets transform 7-17 % of light into electricity, however Nelson (2011) says multiple layers and other improvements have increased efficiencies into the 35-40% range for laboratory experiments.

Roughly about fifty-five percent (55%) of energy in solar irradiance cannot be exploited by majority of PV cells as the energy is either under the band gap or carries power that results in thermal energy. An alternative method to enhance efficiency is employing multiple junctions of p-n which have enough as high efficiencies as 35 %. Nelson (2011) observes that cell efficiencies for silicon goes down as temperature goes up and higher temperatures also threaten the long term stability of the material. Nelson (2011) says therefore PV cells must be kept cool, especially for concentrating collectors.

Goetzberger et al (2003) posits that crystalline silicon currently dominates the market. Plenty supply of a raw material found in sand called silicon which makes it easily available. Goetzberger et al (2003), further highlights that crystalline silicon had a market share of 87.6 % in the year 2000. According to Goetzberger et al. (2003), from solid state physics silicon is not the ideal material for photovoltaic conversion. Silicon has to be very pure and highly crystalline. Goetzberger and Hebling (2000) posits that crystalline silicon currently has a market share of 86 % equally distributed between single crystal and cast silicon. Amorphous silicon holds the other 13 %. Future possibility include thin film crystalline silicon on different substrates. Amorphous silicon CdTe and copper indium diselenide (CIS) have potential for cost effective solar cells.

Nelson (2011), observes that PV cells and modules are classified into three main categories as follows: -

- (1)crystalline silicon cells made from single-crystal or polycrystalline silicon pivot in processes like ingots, cast and ribbon.
- (2)thin film cells constructed from layers of semiconductor material, like amorphous silicon (a-Si), cadmium telluride or copper indium gallium selenide,
- (3)concentrator systems which also include reflectors and lenses.

Mechanism of Operation

Nelson (2011) posits that p-n junction forms solar cells. Nelson (2011) observes that excess electrons at the p-n junction in the n-type material flow to the p-type and the holes thereby vacated during this process flow to the n-type. The in-between junction just behaves like a battery, forming an electrical field where they meet at the surface.

Electrons are caused to change position by the field from the semiconductor out towards to the surface and thereby making electrons available for the electric circuit. Nelson (2011) further says that simultaneously, the holes travel in the opposite direction toward the positive surface where they wait for incoming electrons.

More holes and electrons are formed when the photons are absorbed by PV cells. These holes and electrons now become available as flowing current supplying external load.

Nelson (2011) highlights that the band gap energy for silicon is 1.1 eV.

Goetzberger et al. (2003), says that all PV devices have p-n junctions in a semiconductor between which the photo-voltage is created. When solar radiation or sunlight is absorbed, hole-electron pairs are formed and when their recombination is blocked, they can arrive at the junction where the electric field separate them.

According to Parida et al. (2011), when solar radiation strikes a photovoltaic cell, it gives enough energy to source electrons and raise their energy level to free them.

Boyle (2012) alleges that n-type semiconductor is made from crystalline silicon that has been doped with e.g. phosphorus in such a fashion that the doped material has surplus of free electrons and electrons are subatomic particles with negative electrical charge. Boyle (2012) further says that p-type semiconductor is made from crystalline silicon doped with e.g. boron which causes the material to have a deficit of free electrons and these missing electrons are called holes. Boyle (2012) posits that absence of a negatively charged electron is considered equivalent to a positively charged particle p-type. Boyle (2012) highlights that if we join these dissimilar n-type and p-type semiconductor materials we come up with a p-n junction and this sets up an electric field in the region of the junction. Boyle (2012) says that light can be considered to consist of a system of tiny particles of energy called photons.

Concentrator

Parida et al (2011) posits that in this arrangement, concentrating PV systems employ a large area of lenses or mirrors so as to focus solar radiation onto a small area of PV cells. Tracking is necessary and results in diminished employment of semiconductor material. Semiconductor material is costly. It increases

concentration ratio. Constraints are the cost of focusing, tracking and the cooling of equipment.

Requirements for Ideal Solar Cell Material according to Goetzberger et al. (2003) are as

follows: -

- Good photovoltaic conversion efficiency
- Stability during the long-term
- Simple and deposition technique which is reproducible and appropriate for huge area production
- band structure which is direct
- Nontoxic material and easily available
- Band gap of between 1.1 eV and 1.7 eV

A material satisfying all the above has not yet been found. Thin film material seems to be the best material as they can easily be connected in series.

Problems with PV Technology

Parida et al. (2011) says that at low radiation i.e. less than 400 W/m² reactive power is extracted from transformers and fed into the loads and inverter.

PV History

Goetzberger et al. (2003), highlights that the photovoltaic effect was first noticed by Becquerel. According to Goetzberger (2003), the photovoltaic effect is the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto that system.

According to Goetzberger et al. (2003), Bell laboratories was the place where the first silicon solar cell was made in 1954 by Chapin et al. It had an efficiency of 6 % which was quickly raised to 10 %. Main uses are in space vehicles electric power supplies.

Green (2002) says that Russel Ohl at Bell Laboratory described the pioneering p-n semiconductor junction solar cells. Slowly solidifying melts of silicon formed these junctions. Crystallographic texturing reduces reflection losses. Green (2002) alleges

that most photovoltaic gadgets to date are formed from semiconductor p-n junction. The essential requirement is that the photon should excite electrons to jump from low energy level to a higher energy state. Photovoltaics needs to be excited by light so that electrons move from a ground level to an excited state.

According to Pengju et al. (2024), perovskite thin film has become a leading technology in photovoltaics. Pengju et al. (2024) says that It is typically based on a solution-processed perovskite layer with a film thickness of a few hundred nanometers. Challenges to commercialization include reliability, stability, scalability and industrial compatibility. A solution that mitigates these issues is a thicker film of perovskite on a micrometer scale.

Li et al. (2024), says that another promising photovoltaic technology is organic-inorganic metal halide perovskite solar cells. Li et al. (2024), highlights that organic-inorganic metal halide perovskite solar cells have a power conversion efficiency surpassing 26%. Stability problems hinder their commercialization. Li et al. (2024) posits that high density of defects, ion migration at grain boundaries interfaces and boundaries specially at high operating temperatures causes degradation of the 3-dimensional perovskites. Li et al. (2024) say that growth of low dimensional perovskite layers on the surface of 3 D perovskite thereby creating a perovskite heterojunction gives an effective method to passivate surface defects ad suppress ion migration, thus to a large extent increasing the stability and power conversion efficiency of perovskite solar cells.

Li at al. (2024), observes poor transport of charge carrier across the organic layer is shown by L.D. structures based on large cations because of two factors (1) low carrier movements in organic layers and (2) barriers of energy between organic cations and inorganic frameworks. A trade-off between stability and charge transport efficiency is therefore necessary according to Li et al. (2024). Li et al. (2024) highlights that electron transport of LD perovskites in heterojunction can be optimized through the introduction of strong aromatic conjunction (SAC) molecules

According to Li et al. (2024), in conventional LD/3 D perovskite heterojunction free carriers are located at the conduction band minimum and valence band maximum of the inorganic Pb-I framework respectively and the out of plane charge transport has

to go through a large cationic organic layer due to the long distance between two adjacent inorganic planes conjugated I.D. perovskites which are introduced to overcome this constraint as they consist of aromatic rings to form n-band networks, where π orbitals can form continuous energy bands facilitating carriers to shuttle more efficiently between the inorganic Pb-I framework and cationic organic layer.

Li et al. (2024) observes that superior thermal and chemical stability results from the strong π - π stacking interaction between the aromatic rings of strong aromatic conjunction(SAC).

Advantages of PV over Conventional Generation Systems.

1. There is direct conversion of solar radiation into electricity without going through a thermal process (Garg and Prakash,2000).
2. Reliability, modular, durability and is generally maintenance free (Garg and Prakash, 2000).
3. Quietness, instantaneous response to solar radiation (Garg and Prakash, 2000).
4. Expected lifetime of 20 years or more (Garg and Prakash, 2000).
5. Simplicity
6. Cleanliness.
7. Could be situated at the place of need or point of use and hence requires no distribution and transmission infrastructure,
8. It has a conversion efficiency of 30 %

Disadvantages of PV

1. High costs
2. Intermittency of solar radiation and therefore needs storage batteries (Garg and Prakash, 2000)

Contribution to the World Body of Knowledge

Since solar panels can be adopted as a standard roofing material replacing asbestos, zinc and tiles enforced by progressive municipal by-laws, ‘your roof is your wallet concept’ is hereby proposed in countries experiencing electricity outages like Zimbabwe. The pronsumers need to have bidirectional meters. A pronsumer is a producer as well as a consumer of electricity. The power utility need to deposit payment for excess electricity as a function of time into bank accounts of such pronsumers facilitating ‘your roof is your wallet’ concept as technology advances.

CONCLUSIONS

Price volatility, depletion of fossil fuels and environmental concerns have caused a surge in interest in renewables like photovoltaics. Mainly solar cells are mainly manufactured from an element called silicon that is found in sand. There is monocrystalline and polycrystalline silicon solar cells. The market is dominated by silicon solar cells although some authors say silicon is not an ideal element for solar cells. Solar cells are joined together to make up solar modules, modules into panels and panels into arrays. There is also thin film technology and nanotechnology for P.V. cell production. Solar photovoltaics have no moving parts, no noise during electricity production and no environmental damage. Solar panel field grid-connected have just been introduced in Zimbabwe with solar tracking facilities like the one in Nyabira. The Nyabira Centragrid Solar PV park is a recent development in Zimbabwe Solar panel power stations are becoming imperative because of the need to phase-out coal generation e.g. at Hwange, Munyati, Harare and Bulawayo Power stations in Zimbabwe.

2.2.3 Developments in Parabolic Trough Power Plants

INTRODUCTION



Figure 16: **Parabolic mirror**

The above diagram shows a parabolic mirror with a receiver or solar absorber at its focus.

This section tries to identify developments in literature on Parabolic Trough Collector (PTC) power generation plants. The section highlights that Parabolic trough collectors can be connected directly or indirectly through thermal energy storage tanks to power engines. They are modularized and connected in series and in parallel to form solar collector fields. It posits that the advantages of PTC includes cost effectiveness and ability for cogeneration with fossil fuel power plants as well as with other Concentrated Solar Power generation technologies.

The section says that the parabolic trough power plants are the most mature, tried and tested generation methods among all concentrating solar power stations namely Linear Fresnel, parabolic trough, parabolic dish and Central Receiver Tower Power Plants.

The section posits that PTC power plant consist of the collector field, solar absorber or receiver, thermal energy transfer fluid, heat energy storage tanks(optional), heat engine (turbine-generator set) and heat exchanger.

In conclusions, areas for future research were recommended.

MAIN NARRATIVE

The problem statement is as follows: -

- (a) As a result of climate change, environmental concerns, diminishing of the ozone layer, sustainability and depletion of fossil fuels there is need to move away from fossil fuels. In addition, there is an ever increasing worldwide demand for electricity. The world may be thrown into darkness if coal power plants are scaled down without a viable substitute.

Research Questions are; -

- (a) What are the major parts of a parabolic trough power station?
- (b) How can the efficiencies of parabolic trough be increased?

Objectives

- (a) To identify components of a parabolic trough power plant.
- (b) To identify methods of increasing the efficiencies of parabolic trough power plants

Fugiang et al. (2017) says that there are three classes of energy sources namely fossil fuel, nuclear and renewable energy sources. Sustainability, climate change, environmental problems, depletion of fossil fuels and ozone layer issues have resulted in dislike of fossil fuels and an increased demand for renewable energy. Ahmad et al. (2024) says that fossil fuels are increasingly becoming expensive and it is a finite resource and there is need to shift to renewables. Renewable means that these energy resources get replenished with time naturally. According to Lamba and Dax (2015), energy demand will increase by 25% in the next 20 years. The portfolio of renewable energy includes wind, geothermal, solar generation, hydro, tidal and wave generation. These resources are associated with randomness, intermittency, regional variability and dispersal resulting in difficulties in usage, economical and technical challenges. Thermal energy storage mitigates this disadvantage in Concentrating solar power stations. Garcia et al. (2010) says that a solar intensity of 63 MW/m² exists at the sun and because of the sun-earth geometry, this intensity decreases to about 1kW/m² on the earth's surface. According to Jebasingh and Hebert (2016), one of the freely and abundantly available clean source of renewable energy is solar energy, but Hachicha (2015), says that the solar energy reaching the earth's surface has a problem that it is a generally dispersed energy source and need to be concentrated. Solar power has been proved to be a competent substitute for fossil fuel. Giostri et al. (2012) says that solar energy can play a critical role in future in the replacement of fossil fuel generation for stationary applications- a transition

from a carbon economy to a green economy. One of the greatest challenges of this century is how to maximally extract useful energy from sunlight. Solar output peaks in summer whilst wind output peaks in winter which is good for complimenting each other

According to Freris and Infield (2009), there exists 2 major schemes for the transformation of solar flux into electrical energy namely: -

(a) Photovoltaic(PV) and

(b) Solar thermal system (Concentrated solar power(CSP) plants).

Chang (2007) adds © i.e. employing sunlight to split water into hydrogen and oxygen then the hydrogen could then be fed into a fuel cell for generating electricity.

Freris and Infield (2009) posits that **Photovoltaic(PV)** directly convert solar flux into electricity. Efficiencies of solar panels range from 12% to 18 % although experimental panels have achieved 30% efficiencies.

Solar thermal systems in contrast depend on indirect conversion of solar radiation via heat to electricity.

According to Freris and Infield (2009), 'Fuels of the Fossil type possess one thing in common, they all produce or release carbon dioxide when burnt. The carbon cycle has it as an important part. The unlocking of stored carbon in coal as well as other fossil fuels pushes climate change in undesirable trajectory e.g. increased temperatures globally.

Kotler (2002:56) says that quality is the best assurance of customer allegiance, the strongest defense against foreign competition and the only path to sustained average growth and earnings!

There is need for high quality in the design, operation and maintenance of parabolic trough power plants.

It is now fashionable to construct Renewable power plants. The renewable energy should be safe to humans, friendly to the environment and meet technical specifications and standards. Solar energy has found a superior place among

renewables. There is depletion of fossil fuels like coal due to use since the resource is non-renewable.

Concentrating Solar Power

Concentrating solar power plants employ huge surfaces of mirrors to reflect and concentrate solar insolation onto a far smaller surface of the receiver. Temperatures of about 400 °C are thus achieved. The heat transfer fluid (HTF), inside the receiver is therefore heated to such high temperatures. The heat transfer fluid is normally thermal oil or molten salt (i.e. potassium nitrate and sodium nitrate). Through a heat exchanger the HTF heats water to superheated steam which drives the turbine-generator set and electricity is produced in an environmentally safe manner.

According to Kuravi et al. (2012), says that CSP plants have a big advantage in that they can be coupled to energy storage systems and can also alternatively jointly operate with coal and gas in order to mitigate the intermittency of solar radiation. By furthering the time of usage of the heat engine beyond sun hours, the levelized cost of electricity is reduced for the plant

According to Blanco and Santigosa (2017), 'There are 4 main technologies to collect and concentrate the direct solar radiation into a receiver (a) 2 Line focus concentrators and (b) 2-point focus concentrators

Line Focus Concentrators

(a) parabolic troughs (which is the focus of this paper) and

(b) linear Fresnel

Point Focus Concentrators

(a) parabolic dishes and

(b) central receiver systems known as solar towers.

This paper concentrates on the parabolic trough Collector power plants.

According to Blanco and Santigosa (2017), the following depicts currently existing plants

Power plant Type	% of total in existence
Parabolic trough	90%
Power Tower	5 %
Linear Fresnel	5%

TABLE7

According to Asif (2017), parabolic troughs are modularized and connected in series and in parallel. These parabolic troughs are connected together to constitute a solar collector field and huge areas are necessary for this purpose. Price et al. (2002) posits that the Parabolic Trough generation technology is the most widely deployed and cheapest large-scale solar power generation technology.

According to Lamba and Dax (2015), there are two categories of solar thermal collectors namely (a) flat plate collectors and (b) concentrating collectors. For low temperature applications, flat plate collectors are employed e.g. for producing hot water for domestic purposes (70 °C to 100 °C). Sun tracking is not necessary in flat plate collectors. They work with both direct and diffuse solar insolation. The solar radiation consists of photons which need mirrors or lenses to concentrate for higher energy density and increased temperature levels. Hachicha (2015) highlights that the faceted and parabolic shaped mirrors concentrate solar radiation onto the receiver tube. Concentrating solar thermal collectors are for high temperature applications such as industrial process heat and power generation above 120 °C. Sun tracking is necessary in concentrating solar collectors. They only work with direct sun insolation. According to Hachicha (2015), the faceted and parabolic shaped mirrors concentrate solar radiation onto the receiver tube. Hachicha (2015) says that parabolic trough collectors were initially built for industrial process heat applications.

Blanco and Santigosa (2017) posits that in the solar energy conversion process, mirrors are important in the collection and concentration of solar flux as they are the first and costliest part. The parabolic trough collector field is the most expensive in terms of initial capital costs and during maintenance and operations of the power plant. Reflectors is the other name for the solar mirrors. According to Turehi and Bueno (2017), about 4000 MW of Parabolic Trough power plants has been installed worldwide. Turehi and Bueno (2017) says that the components of a parabolic trough power plant includes solar field, solar absorber, heat transfer fluid system, power block or heat engine, thermal storage and ancillary facilities. According to Asif (2017), the absorber tubes are normally made up of stainless steel with spectrally selective surface coatings that maximize absorption of solar flux and diminishes heat loss by emitting loss radiation. Asif (2017) posits that the oil is pumped through a series of heat exchangers to produce superheated steam.

Efficiency and performance of the Parabolic Trough are key variables that ensure maximum extraction of useful solar energy from the sun. Manikandan et al. (2019) says that the optical efficiency is determined by the property of materials such as the reflectance of the mirrors, transmittance of glass cover, absorptance-emittance of receiver, intercept factor, geometry factor and angle of incidence. Manikandan et al. (2019) highlights that the thermal efficiency is determined by overall loss coefficient which includes conduction, convection and radiation losses. Radiation and convection losses have been diminished by employing an evacuated metal glass tubes and selective surface coatings on the solar absorber. Conduction losses continue to be there and depend on the material of the structure. Experience has revealed that frequent failure of vacuum and accumulation of hydrogen in the absorber and breakages of tubes often occur.

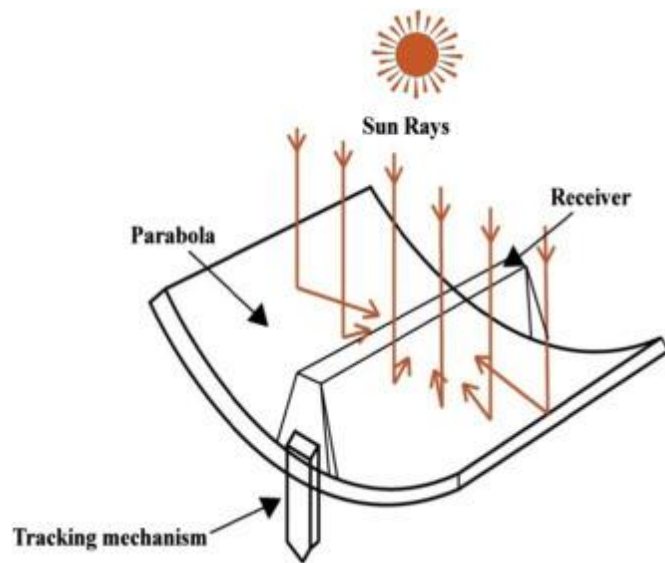


Figure 17

The above diagram shows a mechanism for focusing sunlight using a parabolic mirror with a receiver at its focus.

Belyakov (2019), says that a Parabolic Trough is an assemblage of concave mirrors that reflect and concentrate sunlight or solar insolation onto a solar absorber located at the focus of the mirrors. The trough is parabolic in shape and hence the name Parabolic Trough Power plant. According to Hachicha (2015), the parabolic trough collector comprises of the foundation and pylons, metal support structure, mirrors and solar absorber. The Virtue Glass Tech report (2023) says that the parabolic trough collector consists of the reflector, receiver, the tracking system (sensors, drive and control) and the framework. Ahmad et al. (2024) says that a solar collector is a technology that traps incoming solar radiation. The sunlight is converted to heat through a process of concentration. The absorber tube is constructed from copper or steel painted with a thermal energy resistant black paint. Financial and technological risks for the parabolic trough power plant are expected to be low since the technology is now fully mature. According to Lamba and Dax (2015) 37% of the total installation cost of a parabolic trough power plant is taken by the parabolic trough collectors. This means a lot of effort has to be put in its design in order to make the power plant cost effective. A primary advantage of parabolic trough according to Virtue Glass Tech report (2023) is that the parabolic trough collectors are installed in parallel and can track the sun synchronously and therefore the tracking costs are minimal. Lu et al (2015) says that a parabolic trough collector power plant has convenience of installation, has low cost and attracts simple construction. The optical and thermal properties determine its efficiency.

According to Manikandan et al. (2019), the trough consists of a highly polished glass or aluminum surface with a reflectivity of 95% and 88.5 % respectively.

The encapsulating of the tube is done by either non-evacuated glass jacket or evacuated glass jacket to lower radiation and convection losses. (Manikandan et al. (2019)). A tracking mechanism of either mechanical system or hydraulic along with sensors is used to track the sun by operating in a closed loop circuit to minimize the cosine losses. As mentioned earlier, the collector's overall efficiency is determined by the thermal and optical efficiency of the system and losses from the collector. The Heat Transfer Fluid in parabolic trough is frequently thermic oil operating in the 350 °C to 400 °C range in a Rankine to produce pressure steam that drives the turbine-generator set thereby producing electricity.



Figure 18

Jebasingh and Hebert (2016) posits that a solar parabolic trough comprises of a parabolic reflector plate, a concentric transparent cover and a receiver (heat transfer fluid chamber) Fixed at the focus of a parabolic concentrator is the receiver. A vacuum is maintained in the concentric transparent cover to prevent heat losses. A rigid structure supports the parabolic concentrator and the tracker. The solar tracking system enhances efficiency. According to Price et al. (2002), by 2001 the power generation technology had 127 years of operational experience and operators have gone past the learning curve. Garcia et al. (2010) highlights that concentrating solar systems transform solar flux into thermal energy at the focus. Parabolic Trough in particular focus direct solar flux onto a focal line on the collector axis (Garcia et al. (2010)). Garcia et al. (2010) posits again that a solar absorber tube with a fluid flowing inside absorbs concentrated solar energy from the walls of the tube. In the

process the fluid's enthalpy increases. The collector has a single axis tracking system so that the solar rays falls parallel to its axis. Parabolic Trough Collectors(PTCs) can only utilize direct insolation also called beam radiation or direct normal irradiance. It cannot use diffuse radiation. Direct solar radiation is that component of sunlight which is not absorbed or redirected by particles in the atmosphere like clouds, fumes, humidity and dust particles. The direct normal irradiance reaches and accesses the earth as a parallel beam. Garcia et al. (2010) says that typical aperture widths of parabolic trough are about 6m and total length varies from 100m to 150 m. The concentration ratios range from 20 to 30 and temperatures range from 300 °C to 400 °C.

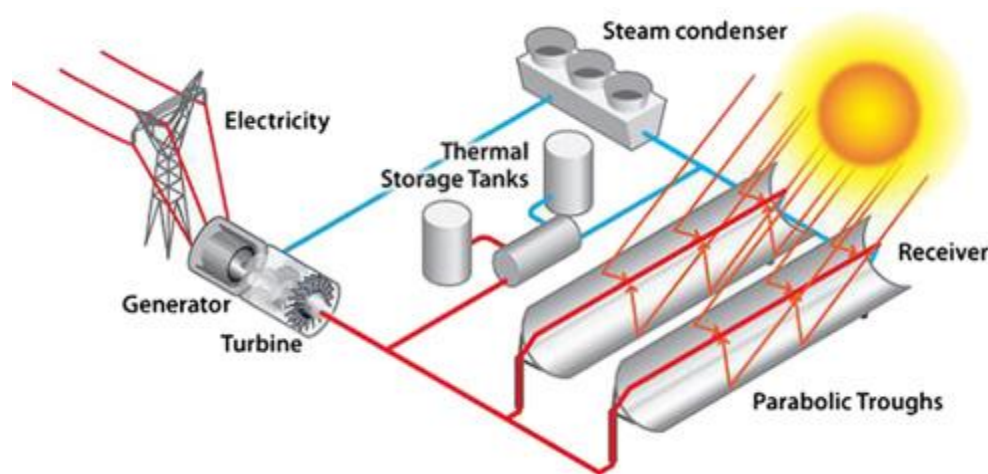


Figure 19

The above is a diagram of a parabolic trough power plant and methodology of functionality.

According to Patnote et al. (2006), the heat transfer fluid at high temperature avails the heat resource needed to drive the Rankine steam power cycle. The heat transfer fluid mass flow rate control strategy helps regulate the temperature of the fluid. Patnote et al. (2006) highlights that the frequently encountered problem is loss of vacuum in the annulus surrounding the solar absorber tube which results in degradation of performance. The hydrogen which accumulates in the annular space also curtails power plant performance. Patnote et al. (2006) further says that the solar field efficiency decreases with temperature whilst the power cycle efficiency increases with increasing outlet temperature.

Fugiang et al. (2017), posits that CSP technologies have the ability to meet thermal and electrical demands. The parabolic trough according to Fugiang et al. (2017) has the following advantages: -

- Cost effectiveness
- It's a mature technology and designers and operators as well as manufacturers are beyond the learning curve.
- Simplicity and easiness of being combined with fossil fuel generators and other renewable power sources.
- Parabolic trough collectors are highly scalable, reliable and possess a long lifespan and are not easily damaged by weather (Ahmad et al. (2024).

According to Ahmad et al. (2024), the disadvantages of PTCs are that they require large land areas and expensive to maintain. PTC are also currently more expensive than fossil fuels (Ahmad et al. (2024).

Jebasingh and Hebert (2016) says that parabolic Trough normally operates with temperature ranging from 350 °C to 400 °C. Jebasingh and Hebert (2016) posits that concentration ratio is the ratio of the effective area of the aperture to the surface area of the solar absorber.

Thermal oil is frequently used as the heat transfer fluid in parabolic trough solar power plants. Fugiang et al (2017) highlights that the traditional heat transfer fluids like molten salt, pressurized air, pressurized water and thermal oil have low thermal conductivity which results in low thermal performance in absorber tubes and heat exchangers. Use of fins made of highly conductive materials in solar absorbers and energy storage tanks is recommended to improve the thermal conductivity. Another method of overcoming the problem of low thermal conductivity is use of nano-sized particles(1-100nm) suspended in the heat transfer fluid. According to Fugiang et al. (2017), the frequently used nano-particles are of Al_2O_3 . Chukami and Heyhat (2023) says that nanofluids are the dispersion of solid particles, ranging from 1 to 100nm in a working fluid in order to enhance the thermophysical properties of the fluid, particularly the thermal conductivity. Chukami and Heyhat (2023) highlights that nanofluids have gained widespread use in various industries owing to their superior heat removal capabilities compared to regular Heat Transfer Fluids. Thermal energy storage tanks are required in order to have capacity to supply energy during the night and during cloud cover.

Conrado et al. (2016) posits that the three heat transfer modes that need to be considered in PTCs are conduction, convection and radiation.

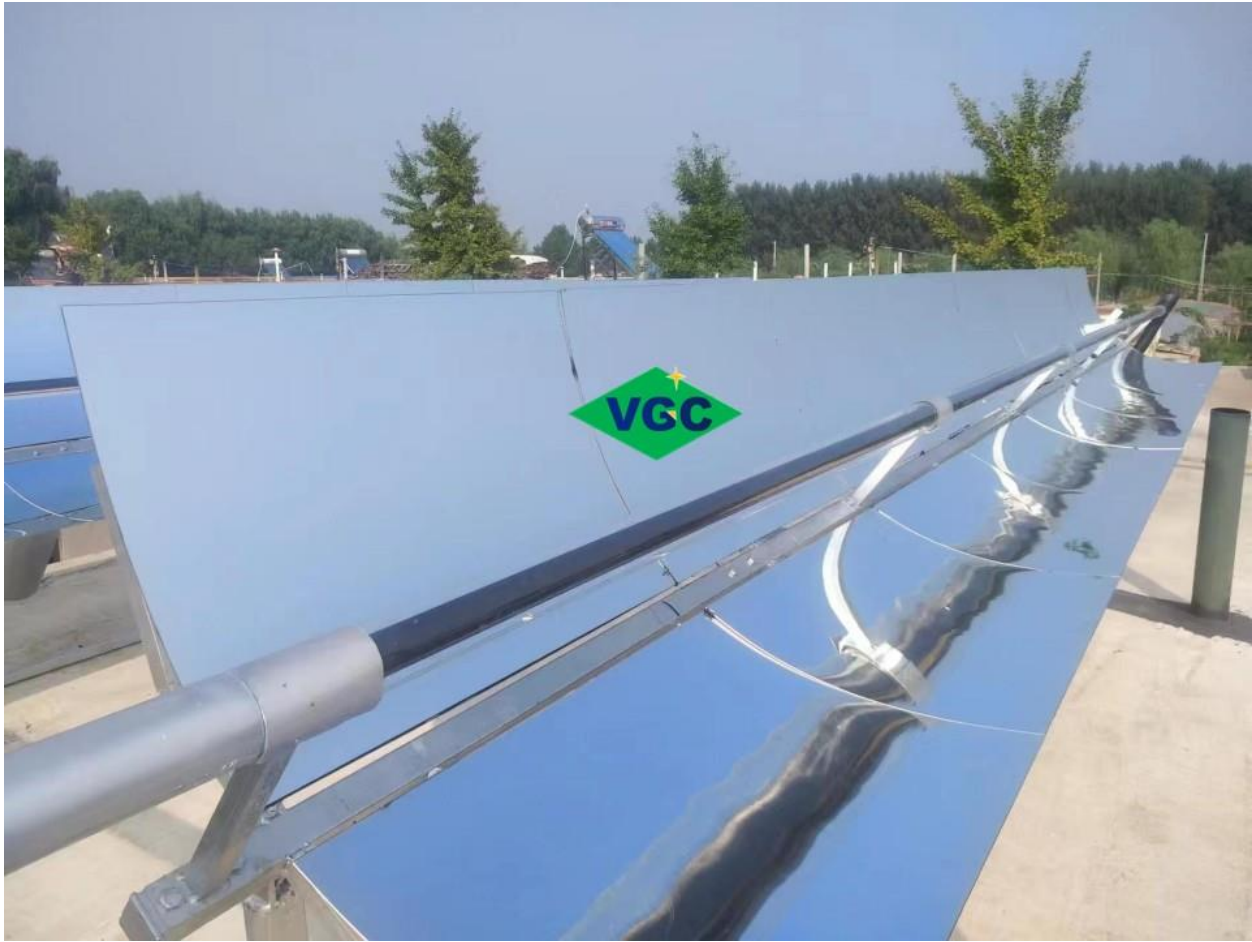


Figure 20

Above is a picture of a unit used to construct a parabolic trough power plant.

According to Giastri et al. (2012), hindrances to wide deployment of parabolic trough generation technologies is the cost of the solar field and temperature limits of synthetic oil which causes poor performance of the steam cycle. (Kennedy, 2000).

Ulrike et al. (2023) says that in the design of parabolic trough power plants, wind loading is a principal contributor to structural design costs. The structures must withstand mechanical forces produced by turbulent wind, whilst the reflector surfaces must maintain optimal and thermal performance. Wind loading on support structures, drives and mirrors can cause deflections and deformations of structural members in mirror assemblage. These deformations can negatively impact performance and reduce the overall plant efficiency. Wind load determine structural lifespan, optical performance and cost of the collectors.

ENERGY STORAGE

Solar insolation is variable, random and is intermittent due to night and day and cloud cover dynamics. According to Asif (2017) in order to diminish the effects of randomness and intermittence of the natural solar resource in parabolic trough power plants and also to enhance Dispatchability capacity, energy storage schemes are necessary.

There are three main types on thermal energy storage schemes namely (a)sensible heat (2) latent heat and (c) thermochemical heat storage technologies. In sensible heat storage, the storage material is heated and the temperature rises with no chemical reaction or phase change. In latent heat storages, the heat energy absorbed does not cause a temperature rise but constitutes latent heat of vaporization or latent heat of melting or fusion. In thermochemical heat storages reversible endothermic chemical reactions absorbs the heat and releases the heat as exothermic reactions.

Examples of sensible heat storage materials include sand, stone, thermal oil, concrete, molten salt (i.e. potassium nitrate and sodium nitrate). Examples of phase change materials include MgCl_2 , KCl , NaCl , NaCO_3 , KCO_3 , LiCO_3
Examples of thermochemical materials include Ca(OH)_2 , CaCO_3 , CuCO_2 .

Receiver Tube

The major component of the parabolic trough technology is the receiver tube or solar absorber also called the heat collector element. According to Hachicha (2015), the receiver tube has an inner steel tube with selective coating surrounded by an anti-reflective evacuated glass tube. There is also a glass to metal bellows. The tube is generally 4m long but can be extended to 150m. The inner steel tube is about 70 mm diameter with a glass envelop which is about 115m outside diameter. Lu et al. (2015), says that the collector efficiency is determined by solar radiation intensity, inlet temperature, flow rate, diameter, condensation rate, pipe length, ambient temperature and wind speed.

Solar Tracking

The sun appears to move in the sky when on planet earth because of two reasons (a) the earth's revolution around the sun (b) the earth's rotation about its axis once per day. This creates an apparent movement of the sun from East to West i.e daily and

seasonal movements. For maximum extraction of solar energy, solar tracking by concentrating solar thermal collectors is necessary. There is single axis tracking and dual axis tracking, but parabolic trough collectors need single axis tracking.

According to Ahmad et al. (2024), the tracking system comprises of the following:

-

- (a) Control unit
- (b) Hydraulic or pneumatic system and
- (c) Electric motor gearbox

A single tracking device can be employed to move a number of PTCs when they are connected in series as a single unit.

Structure and Mirrors

The mirrors found on the market are of glass, polished aluminum or metallized acrylic. According to Hachicha (2015), the mirrors have a reflectance greater than 88% in order to reflect as much sunlight as possible. Hachicha (2015), says that frequently the mirrors are manufactured from low-iron float glass about 4mm thick with high solar transmittance. Hachicha (2015) further highlights that usually the mirrors are silvered on the back and covered with selective coatings. This arrangement has better durability and solar reflectance than polished aluminum and metallized acrylic. Hachicha (2015) posits that reflectance of glass mirrors is 0.93 compared to 0.87 for polished aluminum. In the foundation are pylons with steel support structure to hold the parabolic reflectors. The mirrors are mounted to the collector structure by ceramic pads employing special adhesive.

According to Hachicha (2015) the support structure must meet the following criteria:

-

- Stiffness –rigidness and robustness for the frame to maintain exact geometry at all times.
- Low weight
- One axis tracking which is accurate.

Heat Transfer Fluid

Solar thermal energy is passed onto the power block by the heat transfer Fluid (HTF) which flows through the solar absorber. The selection decision made concerning the heat transfer fluid can determine the type of storage to be adopted for the plant. There are three types of storage technologies (a)sensible heat storage (b) latent heat storage and (c) thermochemical storage technology. The required operating temperature determines the heat transfer fluid to be used e.g. thermal oils are frequently used.

For temperatures above 200 °C. Biphenyl-diphenyl-oxide with trade names Therminol and Dowtherm is frequently used because of excellent stability. It is flammable and therefore safety and environmental protection precautions need to be taken.

Design and Manufacture

The PTC has a straight shape in one direction and curved contours in the other direction. According to Ahmad et al. (2024), for designing a PTC, 3 main parameters are to be taken into account namely (a) the rim angle (b) the geometric Herfildahl-Hirschman index(HHI) and (c) the acceptance angle. The Herfildahl-Hirschman index represents the ratio of the collector cross sectional area to the absorber area (Ahmad et al.2024).

$$\text{Concentration } C_c = \frac{1}{\sin \theta_s}$$

Maximum value =212

θ_s =the spread angle subtended by the sun

According to Ahmad et al, (2024), acceptance angle is the angular range over which the reflected solar rays reach the receiver without involving any movement in the collector. It depends on the outer diameter of the receiver, the focal distance and position.

$$\sin \theta_s = \frac{D_{abso}}{2fp(1 + (\frac{y}{2fp})^2)}$$

Ahmad et al. (2024) highlights that rim tilt depends on (a) focal distance (b) aperture width and (c) arc length.

$$\tan \phi_r = 8 \frac{fp/Aa}{16(\frac{fp}{Aa})^2 - 1}$$

Rim tilt should be kept between 70 ° and 110 ° for optimum performance.

The Herfindahl-Hirschman Index and the spread angle can be estimated using the following equation: -

$$\sin \Theta_x = \frac{\sin \Theta_r}{\pi C x}$$

$$D_{\text{abso}} = A_0 \left(\frac{\sin 0.267 + \left(\frac{\alpha}{2}\right)}{\sin \varphi r} \right)$$

D_{abso} = maximum outer diameter needed to intercept the whole solar insolation where α = dispersion angle (Ahmad et al. (2024)).

The parabolic trough comprises of reflectors, solar absorber, support frame and tracking mechanisms which include sensors and drives (Ahmad et al. (2024))

According to Ahmad et al. (2024), the receiver length at maximum is only 6m long until recently due to technical reasons. The PTC comprises of a number of tubes connected line that adds up to a total of value between 25m and 150 m.

The structure is galvanized so that it is protected from corrosion agents like dust and humidity.

Applications of Parabolic Trough Collectors

Power generation and industrial heating are some of the applications of PTCs. In industrial heating temperatures of between 100 °C and 250 °C are encountered. Other applications include detoxification, desalination, hot water heating, pool heating, pasteurization and sterilization.

Conclusions

The PTC have the advantages of high temperature operation and efficient energy storage which enables day and night generation or even when there is cloud cover. The thermal energy storage facilitates power Dispatchability and brings grid stability. It is a pollution-free power generation technology with high efficiency. PTC challenges includes complexity of controlling and tracking, maintenance and durability challenges. thermal losses in the heat transfer fluid within receiver. It also has scalability and cost effectiveness challenges and high initial installation costs.

The other challenges include tracking accuracy, maintenance and thermal losses. Recent advances in the past decade in parabolic Trough power plants according to U.S. Department of Energy report are as follows: -

- A reduced operation and maintenance cost
- Improvements in trough solar absorber technology
- Improvements in concentrators
- A diminished pumping parasite losses
- Improvements in thermal energy storage technologies for parabolic trough power plants.

The main parts of a parabolic trough power station include parabolic trough collectors, support structure and foundation, tracking system and mechanism, thermal energy storage, heat transfer fluid, working fluid, the heat engine and a heat exchanger

Tracking increases the efficiency of parabolic trough power plants.

Areas for future research

Areas for future research include the area of tracking accuracy and increasing the reflectivity of mirrors. Research into methods of improving the receiver also need to be carried out.

The project now proceeds to discuss parabolic dish plants.

2.2.4 Developments in Parabolic Dish Power Plants

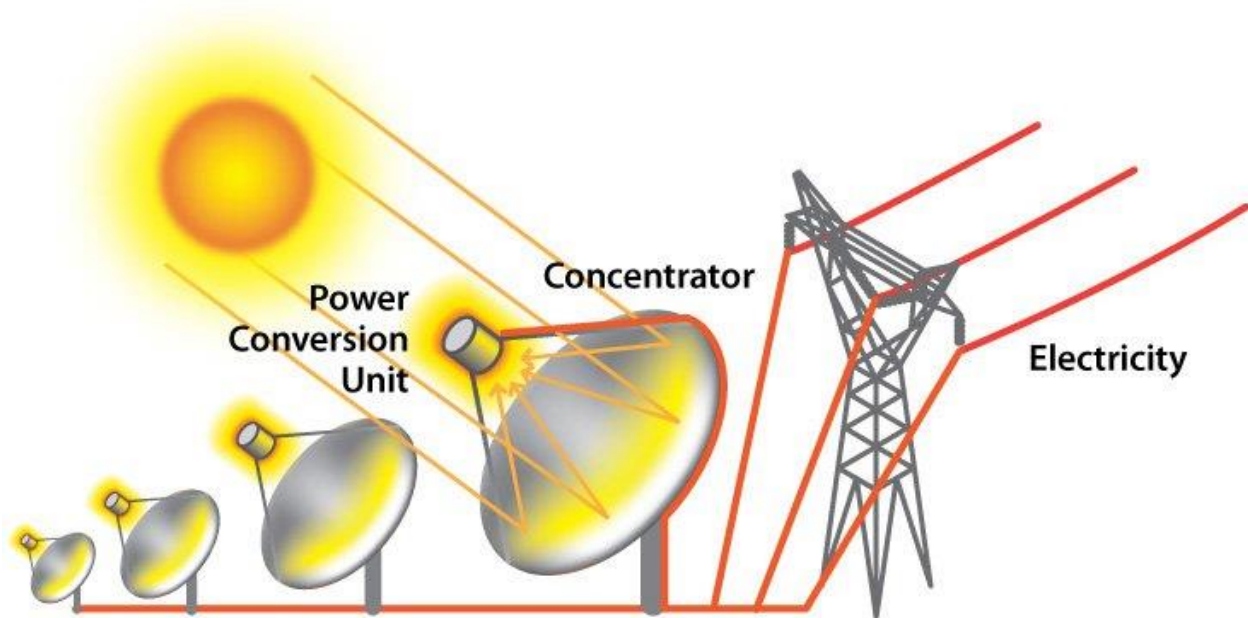


Figure 21 Solar Dish

Above is a picture of a parabolic dish power plant.

INTRODUCTION

This section highlights that parabolic dish technology is among the 4 solar concentration power generation technologies namely parabolic dish, Linear Fresnel, power tower and the parabolic dish. Two of the methods parabolic dish and Linear Fresnel are called line focus and the parabolic dish and power tower are point focus technologies. The section highlights that parabolic dish concentrator is a clean, environmentally friendly and renewable electricity generation method. There has been a surge in interest in renewable energy because of price volatility and depletion of fossil fuels, environmental concerns and worldwide rise in energy demand.

The section investigates developments in parabolic dish power plants. It also discusses the general structure of parabolic dish technologies, their limitations and advantages. The advantages and disadvantages of the parabolic dish are highlighted. Methods for facilitating enhancement of heat efficiencies of the receiver are also briefly mentioned.

The section says that parabolic dish technologies are the most efficient among the four solar concentrating power generation methods but cost limitations hinder their widespread deployment.

The section concludes by recommending areas for future research.



Figure 22

Research Methodology

Textbooks were read and google scholar, dimensions and Scopus journal papers on parabolic dish were consulted as part of the research. Textbooks on solar energy were obtained from Chinhoyi University library and journal papers were obtained online.

MAIN NARRATIVE

Ying et al. (2010) says that sunlight is clean, free, abundant, technically exploitable and renewable in most parts of the world. The sun has capacity to supply the whole of energy needed by the whole world. Fossil fuel price volatilities and depletion, environmental concerns and the ever growing demand for energy has resulted in high interest in Renewable generation technologies. Concentrated solar power(CSP) generation technologies consists of two-line focus and two-point focus technologies and among the line focus is Linear Fresnel and parabolic trough. Point focus technologies include power tower technologies and parabolic dish technologies and

parabolic dish concentrators are the subject of this paper. According to Asif (2017), a parabolic dish employs a concave mirror or a parabolic-shaped dish mirror for concentrating the sun's rays onto a receiver located at the focus of the mirror.

Book Aid International (2009) posits that sunlight is concentrated by the parabolic dish onto a solar absorber at the focus which can either be transformed into electricity or employed directly as heat. Book Aid International (2009), says that the heat energy could be carried for transformation to a central generator or could undergo direct transformation into electric energy at a local generator connected to the solar absorber. According to Book Aid International (2009), the receiver absorbs the solar radiant energy, converting it into heat energy of a circulating fluid.

A generator-engine with direct connection to the solar absorber converts thermal energy to electricity or the fluid is transported along tubes to a central energy transformation system. According to Book Aid International (2009), temperatures as high as 1500 °C can be achieved using parabolic dish systems.

Orosz and Dickes (2017) alleges that a parabolic dish reflector is a type of point focus system having a paraboloid geometry given by a revolution of one half of a parabola around its normal axis. Asif (2017) says that the fluid in the receiver is heated to temperatures of about 750 °C and the thermal fluid so heated is employed to generate electricity using a Stirling engine with moving pistons or a micro-turbine. According to Boyle (2004), the engine itself is placed at the focus of a parabolic mirror in a parabolic concentrator. This has been attempted with Stirling engine and a small steam engine. Boyle (2004) says that Stirling engines were invented in the year 1816. Boyle (2004) posits that although steam engines have difficulties operating with input temperatures greater than 700 °C, Stirling engines, given the right materials can operate at temperatures upto 1000 °C with higher efficiencies. Boyle (2004) alleges that an average of 30 % efficiency over the day have been achieved with experimental solar systems. Mhamed et al. (2024) highlights that parabolic dish concentrators are a highly efficient and clean source of energy.

Ahnaf et al. (2024) says that parabolic dish collectors are mostly used for generating high temperature heat by capturing and converting solar rays efficiently into heat. Parabolic dish concentrators normally use cavity receivers including spiral coils for optimal thermal performance.

Other types of receivers include cylinder and conical shaped receivers.

According to Ahnaf et al. (2024), from numerous receivers with different geometries, the receiver with conical shape and spherical absorber surface were more efficient than other configurations. It provided 50 % higher heat transfer rate

than cylindrical receivers with flat absorber surface (Ahnaf et al. (2024)). By changing the spiral coil pitch the receiver's thermal performance could be improved.

According to Graham et al. (2024), because of high efficiencies compared with other solar concentrating technologies, parabolic dish concentrators are the preferred renewable generation technology although high costs hinder their widespread deployment. There is need for their design to withstand aerodynamic forces they are exposed to due to winds and possible earthquakes.

Graham et al. (2024), says that tilt and wind incidence greatly affect the aerodynamic coefficients and pedestal height greatly influences base overturning moment results while simultaneously affecting the hinge moment at higher incidence values. Pedestal height and wind incidence variations hugely affect the airflow field around the parabolic dish concentrator exhibiting different behavioral characteristics.

Muhammad et al. (2024) posits that the dish structure may change local wind patterns near the cavity of the receiver which also affects the amount of heat loss. The dish has a great influence on the flow in the cavity region.

Mhamed et al. (2024) says that the parabolic dish has high potential as a renewable energy provider for distant and off-grid regions. According to Mhamed et al. (2024), parabolic dish system outperformed photovoltaic systems on experiments done in Algeria in remote locations.

Kumar et al. (2024) alleges that geometrical parameters of the solar absorber or receiver affects the efficiency of the parabolic dish concentrator.

Book Aid International (2009) says that Sodium-heat engines, Brayton-cycle engines and Rankine-cycle engines have been under consideration for schemes employing parabolic dish installed engines, although the most attention has been directed to Stirling engine system.

According to Boyle (2004), a pilot scheme of 60 dishes each driving a 25Kw Stirling engine was constructed and commissioned in Arizona in 2010. High temperatures are necessary to maximize generation efficiency as this also reduces the required land area for a given power output. Boyle (2004) says however low temperature systems have been experimented on and remain of paramount interest.

The parabolic dish is normally employed to produce electricity in the kilowatt range. Asif (2017) highlights that Stirling dish technologies have ability to attain the highest efficiency of all types of CSP systems, but they are not yet deployed commercially.

According to Cherif et al. (2019), Solar dish collectors are receiving increasing interest among power generation researchers because of higher temperatures at the focus and better concentration ratios. Cherif et al. (2019), posits that the receiver's inlet/outlet configuration effects are influenced by geometrical properties of the solar absorber or receiver.

Karimi et al. (2018) says that among the four solar concentration power generation technologies namely parabolic dish, parabolic trough, Linear Fresnel and power tower, solar dish is the most efficient energy transformation technology. According to Karima et al. (2018), the performance of the receiver of the parabolic dish alters due to ambient air temperatures, wind velocity, solar irradiation, heat transfer fluid inlet mass flow rate and receiver geometry. Heat losses mechanisms from the receiver includes conduction, convection and radiation. The walls of the solar absorber facilitate conduction. The opening receiver aperture to atmosphere facilitates convection to the atmosphere.

Karimi et al. (2018) posits that radiative losses from receiver are dependent on temperature of the walls, receiver geometry and optical properties of the walls. Karimi et al. (2018) highlights that some of the receiver geometrical shapes include hemispherical, conical, cylindrical and cubical. According to the same authors, cavity geometries have small effect on system efficiency.

According to Ying et al. (2010), the overall conversion efficiency of parabolic dish/AMTEC system is about 20.4 % with a power output of about 18.54 Kw with operating temperatures of about 1280K in an experiment carried out. Ying et al. (2010), says that Dish/engine schemes have high efficiency, autonomous operation, modularity and are capable of hybrid operation. Ying et al. (2010) further explains that dish/Stirling schemes are the least expensive as they have high solar-to-electricity conversion efficiency of 29.4% as reported in 1984 and 31.25 % as reported in 2007.

According to Orosz and Dickes (2017), the sun's rays going through the collector aperture having a normal incidence is then concentrated onto a solar receiver or reactor situated at the focal point of the dish. For best focus of the solar flux during the whole day, the parabolic dish requires two axis tracking. Usually the concentration ratio is from 500 to 3000 and is therefore ideal for high temperature applications. Normally the dishes are connected together in a thermal solar field and have independent engine units.

Reza and Masoud (2024) says that one of the challenging aspects of solar energy harvesting is the design of effective and novel receivers especially for parabolic dish collectors.

Dincer and Bicer (2018), posits that the dish and the receiver track the sun together and do not experience cosine losses. They have normal efficiencies of 0.90 -0.93 and concentration ratios of between 2000 -5000 and a lifespan of 30 years. According to Dincer and Bicer (2018), the receiver contributes to the moment of inertia of the system.

Cherif et al. (2019), says that there is need to quantify the focal flux distribution in order to estimate optical performance of the solar dish technology. Cherif et al. (2029) posits that Monte-Carlo ray tracing technique is usually employed in the solar energy field in order to ascertain the concentrated solar heat flux and optical distribution of energy.

Ying et al. (2010) highlights that the working fluid is compressed when cold and expands via a turbine or with a piston to produce work.

The 3 main parts of a parabolic dish technology according to Ying et al. (2010) are as follows: -

- Solar reflector
- Solar receiver
- Supporting structure

Blanco and Santigosa (2017), says that a parabolic dish consists of the following: -

- Parabolic dish reflector
- Support structure of the reflector
- Joint attachments on pylons to facilitate dual axis tracking
- Foundations (pier)
- The parabolic dish reflector support structure with solar absorber fixed to it
- Tube-work needed for transmission of the heat transfer fluid on to the solar absorber and to its storage or point of use.

Blanco and Santigosa (2017), alleges that the reflectors can consist of discrete or continuous elements conforming to a parabolic shape. Tracking of the sun is done by both the dish and solar absorber which are normally fixed to the reflector support structure. In order to minimize the shadow posted onto the reflector, the dimensions of the solar absorber have to be optimized. For reduction of the mass tracking the sun, the weight of the solar absorber has to be optimized.

Blanco and Santigosa (2017), posits that normally a Stirling engine is placed at the receiver. Stirling engines consists of piston engines that are heated externally continuously to a gas (frequently helium or hydrogen at high pressure) contained in a closed system. There is cycling of gas between cold and hot spaces in the engine store and released heat is added during the process of expansion and heat is rejected during the process of compression. As an alternative, the solar absorber may contain a thermal transfer fluid that drives an independent thermal engine.

According to Blanco and Santigosa (2017), the parabolic dishes can be laid out as a solar dish field with sufficient spaces in between to minimize shading and collisions of the parabolic collectors during tracking, while facilitating enough access space for maintenance and reduce pipework and parasitic pumping energy for the heat transfer fluid.

Concentration ratios of greater than 2000 are achieved by commercially available solar dish concentrators (Blanco and Santigosa (2017)).

The parabolic dish obtains its name from its shape which is a parabola and is manufactured from reflective material like aluminum. The supporting structure must be able to withstand forces due to weight of the dish and receiver plus wind forces. The purpose of the dish is to trap, collect, reflect and concentrate as much sunlight as possible.

According to Addisu et al. (2024), heat transfer nanofluids such as Al_2O_3 and ZnO synthesized by the sol-gel and conventional precipitation can be used in the parabolic dish concentrators' heat transfer fluid. Nanofluids with Al_2O_3 nanoparticles have better heat transfer capability compared with ZnO based nanofluids (Addisu et al (2024)). According to Reza and Masoud (2024), phase change materials may be exploited for producing a uniform performance for the parabolic dish collectors. Reza and Masoud (2024), says that by increasing the heat transfer fluid flow rate from 60 to 90 kg/hr, the system efficiency increased from 53.5 to 66.4 %.



alamy

Image ID: 2A64NW0
www.alamy.com

Figure 23

Above is a picture of a parabolic dish generating unit.

The Benefits of a Parabolic Dish (According to Tencom report (2024))

- Maximum harvesting of solar thermal energy

- Highest conversion efficiency among all concentrating systems since they are always pointing towards the sun because of tracking.
- High concentration ratio of between 600 to 2000 and is therefore hugely efficient as heat absorption and energy transformation systems

Scalability and can be installed on ground or on rooftops

- Low water usage
- Very efficient and flexible technology
- Less carbon dioxide emissions
- Flexible deployment options
- Overtime cost savings
- Space saving
- Overtime higher return on investment with less upfront costs
- Incredibly portable
- Minimum set up time
- Has modular receiver and therefore collector entities which can either operate as part of a larger system of parabolic dishes or independently.

According to Book Aid International (2009), major parts of the parabolic dish concentrator system are the solar concentrator and the power transformation entity.

Book Aid International (2009) says that for electricity to be generated coming from a central energy convertor, collection of the solar flux absorbed from the solar absorbers and delivered through a thermal fluid to the energy transformation system there is need for circulation of the thermal fluid through the whole of the parabolic dish collector field which makes design issues such as pipe layout and pumping needs emerge. According to Book Aid International (2009), schemes that use small generators at the focus of each dish avail energy in the form of electricity rather than as heat transfer fluid. The energy transformation entity also consists of the heat absorber and the heat engine. Book Aid International (2009) says that the concentrated beam of sunlight energy is absorbed by the thermal receiver which converts it into thermal energy and passes the thermal energy to the engine. According to Book Aid International (2009), a thermal receiver could be a bank of tubes with a cooling fluid circulating through it. Hydrogen or helium are normally used as working fluid in the engine. Book Aid International (2009) says that alternatively heat absorbers are heat tubes in which the condensing and boiling of the intermediate fluid is employed to pass the thermal energy to the engine. The thermal energy from the heat absorber is taken by the heat engine and used to produce electricity. -

According to Pennstate Department of Mineral Engineering report (2024), all solar rays that are parallel with respect to the axis of the parabola are trapped, collected and reflected towards the central receiver at the focus.

Causes of Losses are as follows: -

- Imperfections of the dish alignment
- Non-ideality of reflections

Pennstate Department of Mineral Engineering report (2024), says that many dishes can be arranged in arrays for large scale power generation.

Because of the intermittence of sunlight, energy storage schemes may be necessary. Parabolic dish technologies produce 3 to 25 kilowatts and are useful for modular use.

There are 2 major components of the system as follows: -

- The solar thermal concentrator and
- The power conversion unit

According to Book Aid International (2009), the components of a heat engine generator are: -

- A solar absorber used to absorb the solar thermal flux that is concentrated that is required to raise the temperature of the working fluid in the engine which in turn transforms the heat to mechanical work.
- Connected to the engine is the alternator which is needed to transform work into electric energy.
- An exhaust system for waste heat needed to vent extra thermal energy to the surrounding ambient.
- To match the heat engine's operation is a control system needed to avail solar insolation. Distributed parabolic dish collector schemes are devoid of thermal energy storage technologies, but could be run as hybrid with e.g. fossil fuels when no sunshine is there.

Book Aid International (2009) posits that the frequently employed type of heat engine is the Stirling engine system.

The parabolic dish is installed onto an assemblage which tracks the direction of the sun the whole day as a function of time for maximum solar insolation reflection

The Energy Transformation Entity

It comprises of the heat absorber and the generator or engine. The solar absorber absorbs the solar radiation that will be concentrated and transforms the solar energy to thermal energy and passes the thermal energy to the engine or generator. The heat absorber could be a bank of hollow pipes containing thermal energy transfer fluid normally helium or hydrogen that is also the engine's working fluid. The engine converts heat to electricity. The Stirling engine is the most common type of engine. A Stirling engine employs a hot fluid to drive pistons thereby creating mechanical energy which drives a generator producing electricity in the process.

According to Kumar et al. (2022), among different solar concentrating technologies, parabolic dish is favored because of higher efficiency, low maintenance costs, higher power density and potential for a long lifespan.

Design parameters for a parabolic dish include rim angle of the dish, concentration ratio and the focal length. According to Li et al. (2024), other important factors are reflector shape, reflector material, aperture area, receiver diameter and receiver aperture area sizing. Kumar et al. (2022) says that conical shaped receiver has a high overall optical and thermal efficiency compared with other shapes of the receiver. A ten to thirteen percent of nanofluids in place of normal plain thermal energy transfer fluid increases thermal performance. Kumar et al. (2022) posits that thermal losses are due to geometrical properties and ordination of the receiver.

According to Esfanjani et al. (2022), cavity receivers in solar dish collectors are the best method of obtaining the best thermal performance. Esfanjani (2022) further says that the hybrid geometry of cylindrical-conical can be utilized to attain the high pressure drop and low thermal efficiency of conventional cylindrical and conical cavity receivers respectively.

Esfanjani et al. (2022) posits that performance enhancement of the dish can be obtained by using proper insulation like ceramic fibre. Ceramic fibre can be ideal for this purpose as a result of its excellent heat properties and minimal adverse environmental results.

Aluminum is normally used to make parabolic dishes because of its high strength-to-weight ratio. According to Tencom report (2024), another excellent material is fibre-glass-reinforced-plastic(FRP). The plastic's strength, durability, resilience to corrosion and heat resistance including light weight, easy transportation, simple

installation, high impact strength enables it to resist deformation from strong winds. Its use results in cost saving.

Problems with Parabolic Dish technology according to Ying et al. (2010)

- Wear and tear of moving parts e.g. piston
- Oil leakage from lubrication
- Sealant problems
- Undesirable chemical reactions
- Noise and vibration.

According to Book Aid International (2009), the biggest challenge that distributed dish systems face is to develop a power transformation unit that could possess low maintenance and capital costs, ability to operate automatically, high conversion efficiency and long life.

Areas for future research

There is need for continual research into the possibility of large scale power generation from parabolic dishes and how to reduce manufacturing, installation and operation costs for parabolic dish concentrators.

Conclusions

Parabolic dish technologies are the best in terms of efficient among the four solar flux concentration electricity generation technologies but cost considerations limit their widespread deployment. They can be useful in remote off grid regions and may even outperform photovoltaics.

High temperature operation is good for increased efficiency and also reduces the amount of space required for the plant. Numerous dish concentrators are normally connected together in a solar dish concentrator field for high power generation. There is need for continued research in parabolic dish concentrators in order to reduce their cost.

The project now proceeds to discuss linear Fresnel as a generation option

2.2.5 Developments in Linear Fresnel Power Plants

INTRODUCTION

Because of climate change considerations, emission of greenhouse gases and toxic substances associated with coal generation, there is need to come up with more environmentally friendly and sustainable generation methods. Solar generation of which Linear Fresnel is one such is a possible replacement of injurious coal generation. Linear Fresnel is a combination of certain attributes from parabolic trough and certain attributes power tower generation. Linear Fresnel is a line focus technology with less efficiency than the other three concentrated solar power generation methods namely parabolic trough, parabolic dish and power tower also called Central Receiver Tower power Plant. The Linear Fresnel generation technology is comparatively simple, robust and has low capital costs. It is a less established technology and requires large tracts of land which becomes its downside.

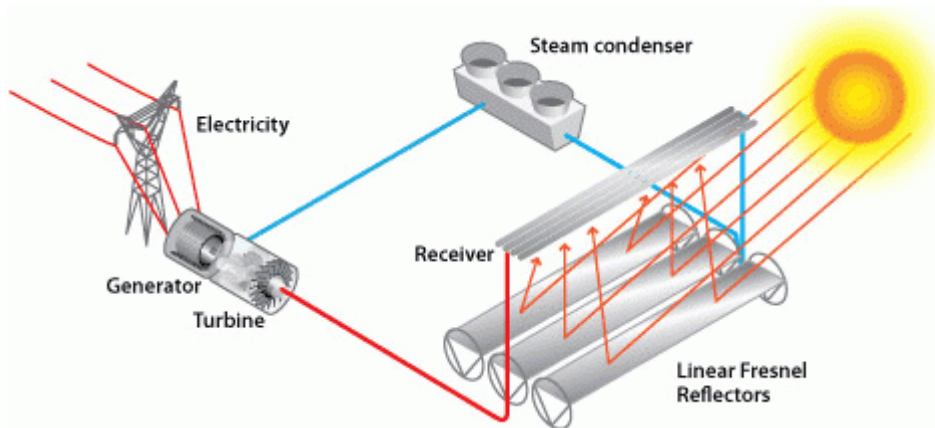


Figure 24

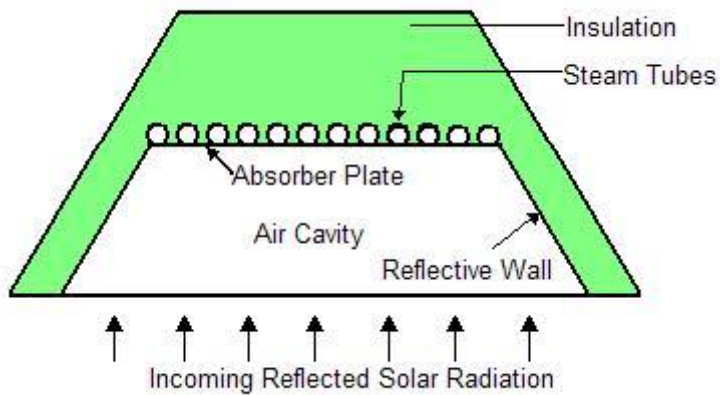


Figure 25

Receiver

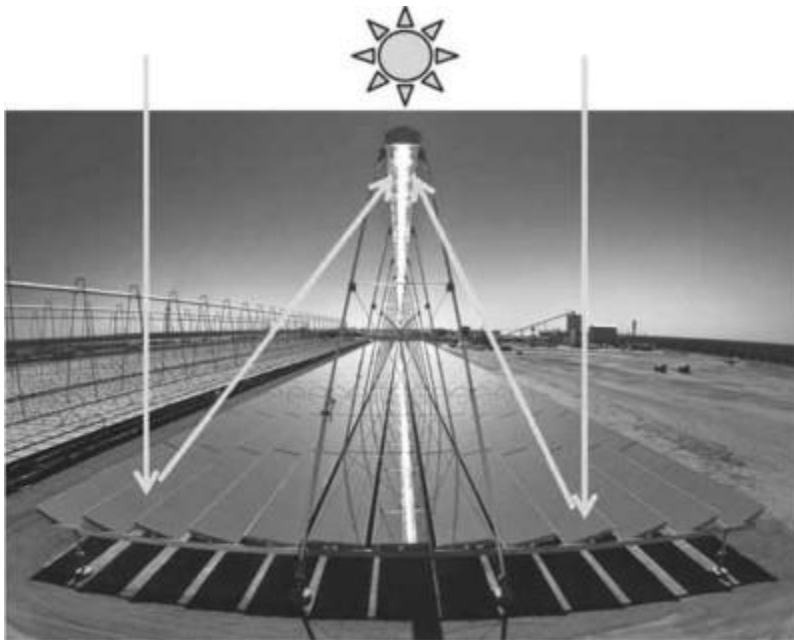


Figure 26

Above are pictures of a Linear Fresnel generating plant. A number of longitudinal reflectors concentrate sunlight on a single longitudinal receiver at the focus of all reflectors.

MAIN NARRATIVE

Rungasamy et al. (2021) says there are 2 methods of generating electricity using solar energy namely (1) photovoltaic power for direct conversion to electricity and (2) concentrating solar energy for indirect generation of electricity through heat as an intermediate form of energy. Rungasamy et al. (2021) posits that photovoltaic is now the cheapest form of electricity production technology because of advances made recently but large scale energy storage difficulties are the problem.

Zhu et al. (2014), alleges that concentrating solar power is a group of technologies that produce heat or electricity with electricity being produced indirectly. According to Singh et al. (1999), the concentration of sunlight is necessary for efficient photo-thermal as well as photovoltaic conversion of solar power. Singh et al (1999) says that Fresnel linear concentrators reduce employment of the quantum of reflecting material and the performance of tubular receiver with Maxorb foil is better than cobalt oxide coated receivers. Singh et al. (1999), alleges that there is a rise in temperature in in oil temperature of Fresnel Linear Reflectors with increase in the number of mirrors, but the increase is not linear.

There exist 2 major categories of sun concentrating power generation schemes mainly point focus and line focus. The line focus technologies include Linear Fresnel and parabolic trough. The point focus includes the parabolic dish and power towers or central systems. According to Bellos (2019), most worldwide projects are based on the line focus technologies Rungasamy et al. (2021) posits that line focus technologies constitute 81% of current Concentrated Solar Power (CSP) capacity worldwide. Linear Fresnel has a linear concentrator and linear solar absorber. The concentrator has a segmented parabolic shape near the ground level. The location of the receiver is at the focal line or very near it. Rungasamy et al. (2021) alleges that point focus technologies employ dual axis tracking whilst line focus technologies employ single axis tracking to concentrate solar rays onto a solar absorber or receiver. Point focus technologies attain higher temperatures than line focus technologies Rungasamy et al. (2021)). According to Rungasamy et al. (2021), point focus technologies are more complex and more expensive than line focus technologies.

The parabolic trough constitutes 72% of global CSPs (Rungasamy et al (2021)). According to Morin et al. (2012), Linear Fresnel Reflectors(LFRs) have cost reduction potential.

Zhu et al. (2014) says that LFR use an array of low-profile, flat or near flat primary reflectors and a fixed solar absorber assembly that incorporates one or more linear receiver tubes and an optimal secondary reflector. The sun is tracked by the reflectors whilst the solar absorber remains fixed during the day.

Rungasamy et al. (2021) highlights that 56 % of all new renewable power stations built in 2019 were less costly than their fossil fuel counterparts. Rungasamy et al. (2021) further says that renewables have experienced the largest annual growth in investment in the last three years as seen in 2020.

Qazi (2017) says that the Linear Fresnel Reflector (LFR) is pivoted or foundationed on a principle between the Central Receiver Power Tower (CRPT) power plant and parabolic trough concentrator systems. Arunkumar (2023) highlights that Linear Fresnel Collector was named after a French physicist named Augustin-Jean Fresnel who made huge contributions to the optics field.

According to Berrada et al. (2021), Linear Fresnel power generation technology employ flat mirrors that trap, collect and concentrate sunlight into a tube or receiver passing through the focal point of the reflectors. Inside the pipe or tube will be flowing water which becomes steam due to heat and is used for power generation. Zayed and Elshheikh (2022) says that the Linear Fresnel Reflector consists of an arrangement or configuration of linear arrays that reflect and concentrate the sun's rays onto a connected linear solar absorber or receiver. According to Sun (2021), Linear Fresnel reflector (LFR) emerged last among the four mainstream concentrating solar power systems but has rapidly developed in recent decades. Its concept is obtained from the Linear Fresnel Lens (Sun (2021)). Sun (2021) posits that the linear Fresnel reflector has a fixed receiver with discrete slightly curved or flat concentrating mirrors which are installed on the ground having a single axis sun tracking system. Sun (2021) further highlights that the concentration ratios of the LFR technology can reach 100 by employing secondary concentrators. Bellos (2019) says that the major cause of losses in a Linear Fresnel reflectors are the optical losses.

When sunlight is reflected from a very large surface area onto a very small area, it is said to be concentrated. Concentration increases solar flux density or solar flux intensity.

According to Jin and Hong (2012), in LFR strips of mirrors rotate around independent parallel axis to reflect sunlight onto a fixed linear solar absorber or receiver. Jin and Hong (2012) says that operating temperatures are between 50 to 300 °C and concentration ratio of about 10 to 40 are normal.

According to Lovegrove and Stein (2021), the fixed receiver does not only avoid the need for joints for movement of the heat transfer fluid which rotates but also help in reducing convection losses from the receiver by using permanently downward facing cavity of the receiver. It has less supporting structure than parabolic trough collector(PTC) closer to the ground. Lovegrove and Csiro (2012), says Linear Fresnel reflector technology produce solar linear focus on a downward facing fixed receiver mounted on a series of small towers. According to Mahopac (2022), LFR scheme comprises of a lot of curved mirror strips on each side of a tubular receiver. One disadvantage is shading effect between adjacent reflector mirrors. The compact Linear Fresnel Reflector employs multiple receivers within the vicinity of its reflector mirrors to reduce above disadvantage.

Berrada et al. (2021) says that the arrangement of LFR is done in the same manner as parabolic trough concentrator solar power systems forming a large number of relatively long arrays aligned in a north-south orientation for maximization of the collected solar energy. According to Berrada et al (2021), the Linear Fresnel scheme has stored energy with potential to either be used directly for immediate power generation or for later use through energy storage schemes.

Zayed and Elsheikh (2022) alleges that in order to get a high solar radiation concentration, an elastically rounded or plane reflector is employed as a secondary reflector in order to enclose the top side of the absorber tube. The concentration ratio of the parabolic trough concentrator is higher than that of Linear Fresnel. Zayed and Elsheikh (2022) says that the linear Fresnel is better from an economics point of view when compared with parabolic trough collectors because it possesses one absorber or receiver mounted onto ground and all reflectors are also fixed which diminishes mounting and installation costs. Bellos (2019) posits that the solar absorber of a LFR is fixed and doesn't move and is situated some several meters from the ground level.

According to Zayed and Elsheikh (2022), Linear Fresnel has lower working temperatures and lower efficiencies compared to other concentrating solar collecting technologies because of its low concentration ratios. The linear Fresnel reflectors are the cheapest and operate in a temperature range of upto 300 °C. Their concentration ratios according to Bellos (2019) is between 10 to 50. In order to prevent the

shadowing effects on reflectors, the linear Fresnel reflector technology requires a large space which is one of its disadvantages. This handicap can be diminished by increasing the receiver tower height, but this will upscale or uplift the system's cost.

Qazi (2017), posits that LFR may comprise of an energy storage scheme e.g. sensible heat storage, latent heat storage or thermochemical heat storage.

According to Sun (2021), the largest LFR CSP in the world operates upto 125 MWe and employs direct steam generation and has been operating for years.

Bellos (2019) says that normal designs involve trapezoidal cavities and evacuated tube receivers.

The Linear Fresnel Reflector produces useful energy for high and medium temperature levels of less than 500 °C. It is a minimal cost technology with enough thermal performance. According to Bellos (2019), solar thermal collectors are the gadgets that transform solar rays' incident on it into valuable heat whereas photovoltaics convert sun's rays directly into electricity. Heat can be stored for later use in large quantities better than electricity a factor which advantages concentrated solar thermal power plants than photovoltaics. The use of solar concentrators is to concentrate solar radiation onto a receiver.

Rungasamy et al. (2021) says that because of a large number of mirrors moving independently of each other within Linear Fresnel Reflector field, adjacent mirrors can interfere solar-wise with each other optically thereby lessening the amount of solar radiation reaching the aperture of the receiver. There is need for the optical design to reduce the optical interference between the different parts.

Compact Linear Fresnel

Rungasamy et al. (2021) says that Mills and Morrison in 1998 proposed interleaving the edges of two standard LFR mirror fields. Rungasamy et al. (2021) posits that by alternating targets at the edge of the field dissimilar target angles were created which reduce shading and blocking between adjacent mirrors and allowed mirrors to be more closely packed. This was ideal where space limitations and land costs were high. Mills and Morrison (2000) highlights that in compact linear Fresnel Reflectors there are numerous parallel linear solar absorbers raised on tower structures that are sufficiently close for individual mirror rows to have the option of guiding reflected solar radiation to two alternative linear receivers on separate towers and this allows

for densely packed arrays. Mills and Morrison (2000), says that the alternating mirror inclinations can be set up in such a way that blocking and shading are prevented whilst maximizing ground coverage. According to Mills and Morrison (2000), better designs would also employ secondary optics that will lessen tower height needs or requirements. The prevention of large mirror rows spacing and absorber heights is a useful cost issue in determining the cost of ground preparation, array substructure cost, tower structure cost, steam line thermal losses and steam line costs (Mills and Morrison (2000)).

Mills and Morrison (2000) says that in Compact Linear Fresnel Reflectors there would be numerous parallel linear absorbers that are sufficiently near individual mirror rows to have the option of directing reflected sunlight to two linear absorbers on separate towers.

MAJOR COMPONENTS OF LFR

1. Linear reflective mirror
2. Receiver tube
3. Transmission system

The linear Fresnel, according to Wang (2019), can be considered a simplified parabolic trough energy generating system. Wang (2019) says that the parabolic trough collector is replaced with a surface mirror. The mirror has a small distance to ground, a simple structure, low wind load, an intensive layout and higher land use efficiency.

Wang (2019) posits that vacuum treatment of the receiver tube is not required thereby reducing costs and technical difficulties. Wang (2019) says that the LFR has low system efficiency because of lower operational temperature and low concentration ratio.

Lovegrove and Stein (2021) alleges that in order to enhance ground use and optical efficiency, compact linear Fresnel reflectors employ multiple receivers for each set of mirrors thereby ensuring that mirrors have different inclinations for them to target different adjacent receivers. Lovegrove and Stein (2021) says this permits higher packing density of the mirrors which minimize land use and increases optical efficiency. Upto 2019, LFR employed in the commercial sector used direct steam

generation in the receivers. New systems with molten salt are now emerging (Lovegrove and Stein (2021)).

According to Fraia and Vanoli (2022), the mirror surface is divided into a series of narrow, long, multiple, shallow curvature facets of mirrors which track and follow the sun focusing the sun's rays onto a fixed solar absorber pipe.

Disadvantage of Linear Fresnel (According to Arunkumar (2023))

- It has lower efficiencies compared to the other four CSP technologies
- It requires large pieces of land
- It is a less established technology compared with PTCs.
- Low optical performance in the primary solar collector field (Rungasamy et al. (2021))
- LFRs have less optical and thermal efficiency than parabolic trough collectors (PTCs) (Zhu et al. (2014))

Advantages of Linear Fresnel Collectors (According to Arunkumar (2023))

- Have simpler mechanical operations and easier to install
- Are cost effective compared to parabolic trough-low investment cost technology.
- Can be integrated into some existing electricity generation plants e.g., fossil fuel, photovoltaic or hydro.
- Have low profile and can be designed with a smaller environmental footprint
- Lower investment costs
- LFR can operate in a large range of temperature levels which permits wide application areas Bellos (2019)
- It is a very promising concentrating technology for high and medium temperature applications (Bellos (2019))

Advantages of Linear Fresnel (According to Sun (2021))

- Simple
- Small wind load. Wind load and land utilization is low (Bellos (2019))
- Its robust
- Low capital cost
- Flexible design

- The linear Fresnel reflector is superior to parabolic trough technology because the receiver is stationary and it has higher safety and reliability.
- According to Abbas et al. (2013), LFR can attain higher concentration s than PTC and have great potential to reduce costs.
- Abbas et al (2013) says that because of tinnier slightly bent mirrors and fixed receiver, LFRs do not incur disadvantages suffered by parabolic trough schemes such as heavy structures, receiver failure and oil leaks.

According to Fraia and Vanoli (2022), Linear Fresnel reflector technologies are ideal for high temperature, low and medium temperature applications. Mills (2012) says that peak performance of LFR is now approaching that of PTC in the case of the non-secondary reflector. Mills (2012) further emphasizes that LFR energy production costs are going down quickly compared to parabolic trough collectors(PTC).

Applications for Linear Fresnel Reflectors(LFRs)

- Heating production
- Industrial heat
- Chemical processes
- Desalination
- Power generation

Zhu et al. (2014), says that LFRs are ideal for high thermal level CSP applications for electrical energy generation at power utility scale.

According to Rungasamy et al. (2021), Linear Fresnel Reflectors have not yet reached commercial maturity and therefore a lot of research into them is required. Designs for pinnacle conditions is designing with the assumption where there is no shading or blocking for a vertical sun.

Zhu et al. (2014), says that the torque load of the wind is proportional to the square of the height of the mirror.

Edouard et al. (2023) says that solar field inclination and orientation are the variables that greatly affect the optimal performance of linear Fresnel Collectors. Zadeh et al. (2024), posits that field configuration has a huge effect on optical efficiency in

Linear Fresnel reflectors and constant, optimal and variable distance configurations exist.

Nelson et al. (1975) alleges that the linear Fresnel lens concentrator is excellent during the period of time within 1 hr of solar noon. According to Nelson et al. (1975), Enhanced refraction due to enhanced incident angles of the solar insolation causes a sharp-drop-off energy given to the absorber at the other hours of the day.

Conclusions

Linear Fresnel is a less established technology and requires large tracts of land for construction. It is simple to construct and to operate, robust and has low capital costs.

Gaps IDENTIFIED IN LITERATURE

1. The actual calculations of sizing thermal energy storage tanks.
2. The calculations of sizing a 500 MW Central Receiver Tower power plant components and a power plant suited specifically for Zimbabwe.
3. The details of how to measure reaction kinetics for thermochemical energy storage tanks.
4. Designs of control room
5. The exact details for solar tracking in power tower power plants Heat/Thermo safety rules.

2.2.7 CENTRAL RECEIVER TOWER POWER PLANT (ALSO CALLED THE SOLAR POWER TOWER)

The project is about designing a 500 MW Central Receiver Tower Power Plant which is the selected Concentrated Solar Power Plant.

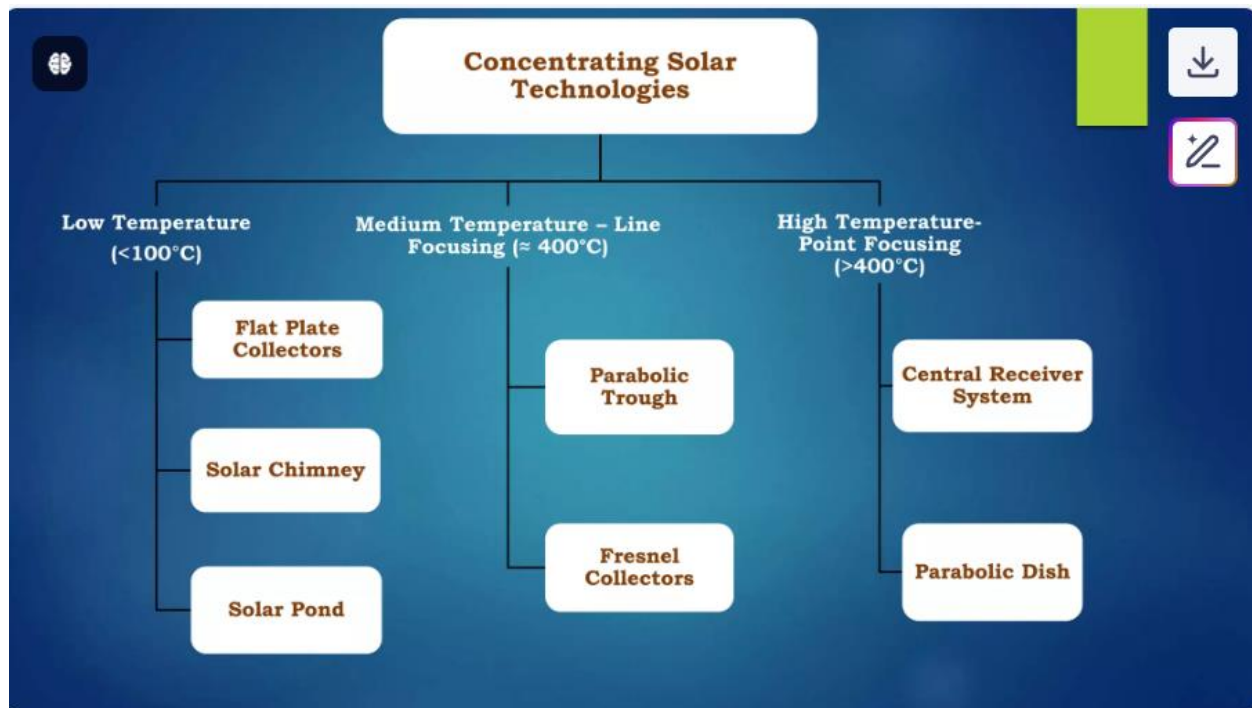


Figure 22 a

According to Anand (2025), solar thermal electricity is comparatively new and has demonstrated huge potential for clean energy and sustainable development. About 80-90 % of collected sunlight energy is absorbed by the Heat Transfer Fluid (HTF) in a central receiver on top of a tower. Mahdi and Khudheyer (2018) says that the absorber collects the thermal heat being reflected from the mirror field and transmits it to a heat transfer fluid which maybe water or molten salt.

Wagner et.al. (2010) says that the process of design for Central Receiver Tower power plants is different from other concentrated solar power schemes e.g. parabolic trough and parabolic dish that are modular in design. CRT design need ascertainment

of the layout of heliostat mirror field and geometry of the receiver that have the highest long term sunlight collection per unit cost.

Anand (2025) says that CRT power plants consists of the following: -

1. Heliostat field
2. Central tower
3. Receiver
4. Storage tanks
5. Working fluid and or Heat Transfer fluid
6. Turbine/generator set

PennState (2025) highlights the fact that Central Receiver Tower(CRT) Power plants concentrate sunlight rays onto a distant central solar absorber. It comprises of many heliostat tracking mirrors located in a field surrounding a major external solar absorber installed on a tall tower structure. It is capable of attaining much higher thermal levels because of higher concentration levels than linear systems. PennState (2025) posits that the resultant heat is used to produce electricity whilst the other thermal energy is stored in molten salt e.g. potassium nitrate or sodium nitrate. CRT are generally large-scale stations that are constructed to power a steam cycle. The tower supporting the receiver is centrally and strategically positioned to collect as much sunlight energy as possible according to PennState (2025).

This power plant has a tall tower surrounded by heliostat mirrors having a very large area that reflect the sun's rays onto a receiver or solar absorber having a far smaller area on top of the very tall tower thereby concentrating the solar flux. This enables realization of temperatures as high as 1000 °C at the receiver. The components of a power tower are as follows: -

1. Tower for allowing the absorber to be accessible by all sunlight from all heliostat mirrors without obstruction.
2. Receiver also called solar absorber for absorbing and concentrating the solar flux from heliostat mirrors.

3. Heliostat mirror assembly-for trapping and refocusing of sunlight. The heliostat Mirror assembly also provides a large surface area for sunlight to fall onto.
4. Thermal energy storage tanks-for storing heat energy for enabling electricity generation at night and also during cloud cover
5. Heat exchanger-for enabling transfer of heat energy from the thermal energy transfer fluid (molten salt) to working fluid (i.e. water)
6. Condenser-for converting steam to water thereby enabling the cycle to start again.
7. Turbine-to enabling the conversion of steam pressure into rotational kinetic energy and for forcing rotation of the generator.
8. Generator-for generating electricity
9. Step-up substation-for stepping up the voltage e.g. from 30 kv to 330 KV for enabling transmission with minimum heat losses
10. Cooling tower-for cooling steam

Advances in Clean Energy Technology (2023) says that there are 3 main configurations for CRTs as follows: -

1. Complete surround of the receiver tower with the heliostats. The receiver is normally cylindrical.
2. Heliostats situated North of the absorber tower (in Northern Hemisphere) and absorber has an enclosed surface for heat transfer.
3. The heliostats are situated south of the receiver tower (in southern hemisphere), receiver has a vertical plane and North-facing surface for heat transfer.

According to Advances in Clean Energy Technology (2023), CRTs are one of the highest in terms of efficiency in trapping and harnessing sunlight heat energy. The heliostat field is the major component of the CRT plant (incurring 50 % of capital costs and responsible for 40 % of overall losses of energy). To minimize land use, environmental impact and capital costs it is necessary to design an efficient heliostat field. Advances in Clean Energy Technology (2023) says that CRT power plants

have huge potential of replacing coal power plants. It is likely to evolve into a technology of choice in future. There is need for improving the heliostat field, the solar absorber and the power block's efficiency and cost ensure reduction. CRTs provide cheaper electric energy compared to trough and dish technologies and perform better.

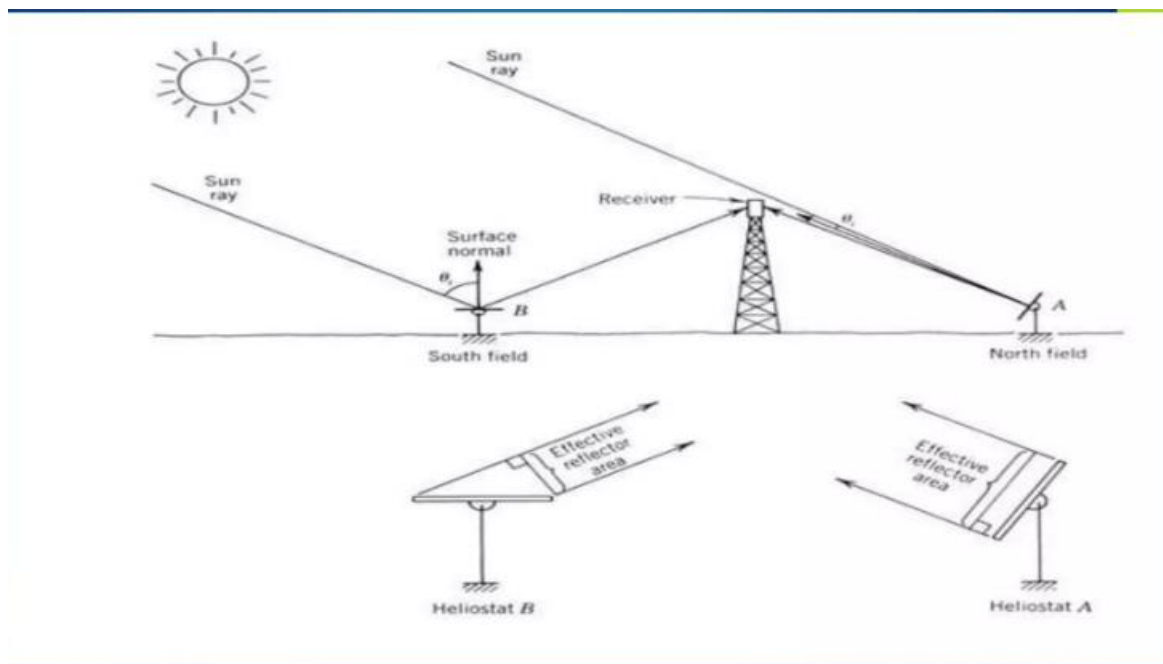


Figure 22b

Below are photos and drawings of the Central Receiver Tower Power Plant demonstrating mode of operation.

Advances in Clean Energy Technology (2023) says that CRT power plants operate at about 550°C . It says that CRT systems possess a huge potential for mid-term reduction of cost of electric energy in comparison to parabolic trough since they permit numerous intermediate steps between the integration in a Rankine cycle up to higher cycles of energy using gas turbines at temperatures higher than 1000°C which leads to higher outputs and efficiencies.



Solar Power

Tower, photo courtesy of [NASA.gov](https://www.nasa.gov)

Figure 27

Mirrors will be concentrating heat on the tower

According to Advances in Clean Energy Technology (2023), a CRT power plant basically consists of 3 major parts as follows: -

1. Heliostat field
2. Solar absorber
3. Power conversion system with temperatures ranging from 250 °C to 1000 °C.

CRT power plants have been under continuous development since 1965.

The solar receivers are manufactured from material that can withstand high temperature changes and higher energy density e.g. metal alloys or ceramic (Advances in Clean Energy Technology, 2023).

There are 3 types of receivers namely:-

1. Volumetric receivers
2. Cavity receivers
3. Particle receivers

The Bryton cycle, Rankine cycle or combined cycle are employed to convert energy from thermal to electricity (Advances in Clean Energy Technology, 2023).



Figure 28

Above is a picture of a Central Receiver Tower power plant. At the centre and around the tower are thermal energy storage tanks, turbine-generator room and housing for heat exchanger and condenser.

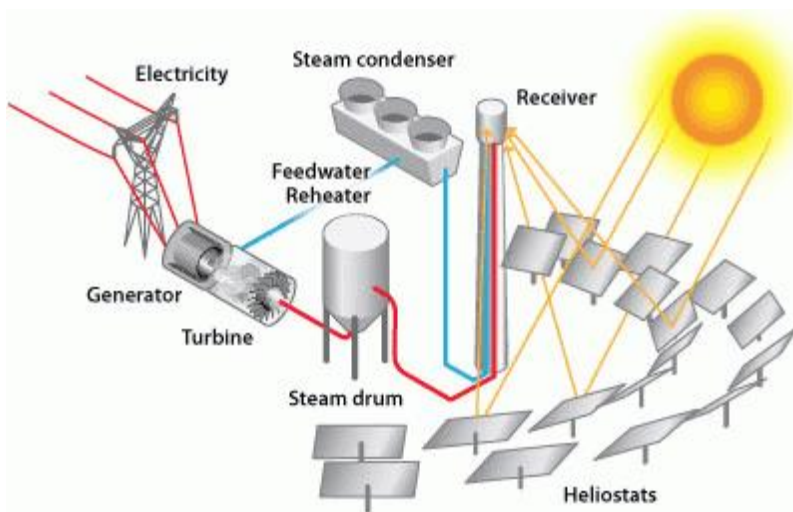


Figure 29

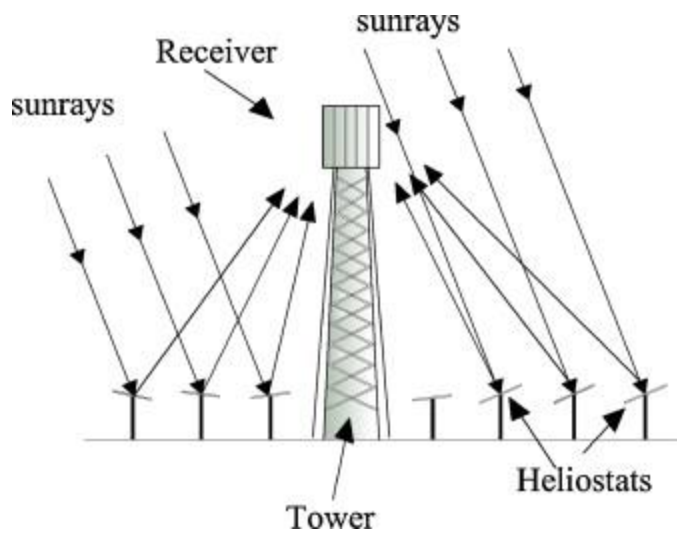


Figure 30

Above are diagrams showing the functionality of the Central Receiver Tower (CRT) power Plant

PennState (2025) says that because of large geographical areas required by CRT power plants, issues of land use, higher capital costs and environmental impact arise. Deserts, flat arid regions and areas with plenty sunshine have huge potential for such plants since they have lower land value. PennState (2025) emphasizes that the current biggest solar thermal station in the world is on the border with Nevada in Southern California and its called Ivanpah. It has 3 main towers and heliostats measuring about 2.5 million square meters of mirrors. The installed capacity at Ivanpah is 377 MW. PennState (2025) posits that it is the only operational plant with a capacity larger than 20 MW. The world has limited experience on these plants although Spain and U.S.A. possess much more experience with these plants.

According to Anand (2025), the following are CRT Characteristics

- Commercially proven
- Excellent performance for large capacity and high thermal levels
- Feasible on non flat sites
- Capable for heat storage

- Flat mirrors/ slightly concave
- Point focusing
- Thermal levels (600-800 °C)

ADVANTAGES OF A CENTRAL RECEIVER TOWER POWER PLANT

- It has a capacity factor of almost 60.7 % and efficiency of 18.97 %.
- Capability of attaining higher temperatures with power tower power plants resulting in higher efficiencies.
- The heat storage costs are brought down which results in lesser geographical land needs when compared with other CSP power generation schemes.
- Higher potential for cost reduction and improvement of efficiency.
- Can use heat storage which helps enhance matching of supply and demand.
- Lower operating costs
- No radioactive nuclear waste like in Nuclear power plants.
- Has huge potential for integrating with coal power plants
- Can attain higher thermal levels (upto 1000 °C) and have higher efficiencies as a result.
- Has potential for cost reduction and improvements in efficiency.

DISADVANTAGES OF CRT POWER PLANTS

- Higher construction and installation costs
- It is complex
- Slightly more expensive than PV
- Need a considerably large amount of space compared with for example nuclear generation or coal generation.
- Low energy-density compared with e.g. nuclear generation



Figure 31



Figure 32

Zhou and Zhao (2014) posits that a solar tower power plant comprises of a heliostat field, tower, solar absorber, heat transfer fluid, thermal energy storage tanks and the power block or power engine. They posit that the heliostat field encompass radial staggered and cornfield.

Cosine factor

The efficiency depends on both the sun's position and the location of the individual heliostat relative to the receiver.

$$\cos 2\theta_i = \frac{(z_0 - z_1) \sin \alpha - e_1 \cos \alpha \sin A - n_1 \cos \alpha \cos A}{\left[(z_0 - z_1)^2 + e_1^2 + n_1^2 \right]^{1/2}}$$

where α and A are the sun's altitude and azimuth angles, respectively, and z , e , and n are the orthogonal coordinates from a point on the tower at the height of the heliostat mirrors.

Yearly average cosine factor for a north heliostat field is 0.71 – 0.91

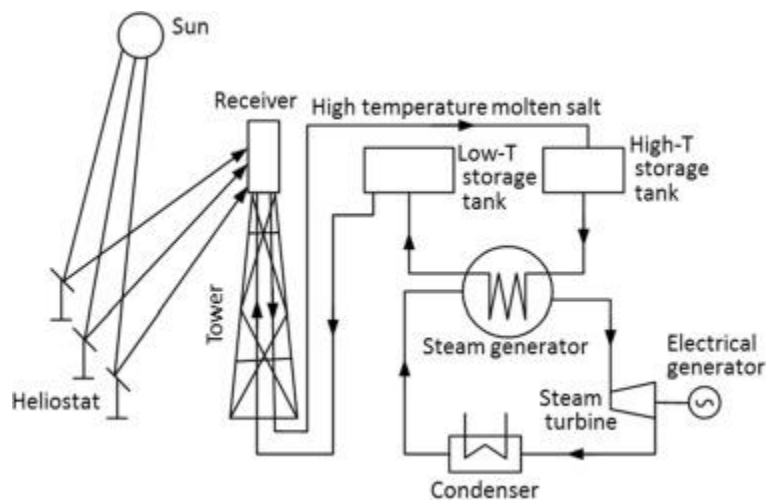
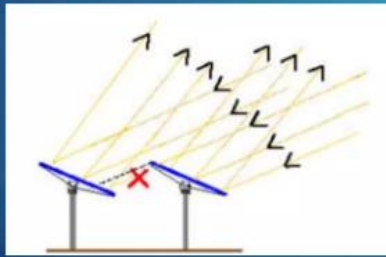


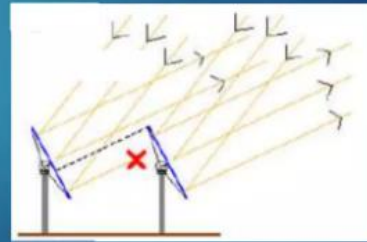
Figure 33

Shading and blocking

- Shading occurs at low sun angles when a heliostat casts its shadow on a heliostat located behind it. Therefore, not all the incident solar flux is reaching the reflector.
- Blocking occurs when a heliostat in front of another heliostat blocks the reflected flux on its way to the receiver.
- The amount of shading and blocking in a particular field layout is a function of the heliostat spacing, tower height, and sun angle



Shading



Blocking

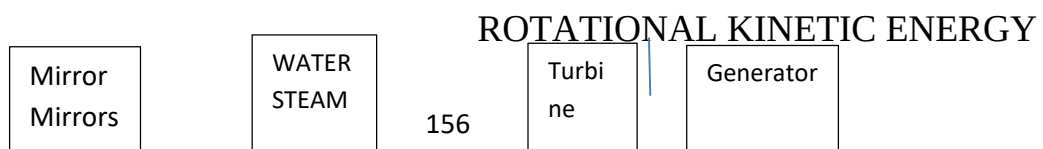
In Concentrated Solar Power, sunshine is the input and heat is the output and the process encompass mirrors'.

Sunlight → Heat → Mechanical Energy (pressure) → Rotational kinetic energy → electricity



Figure 34

Or rather

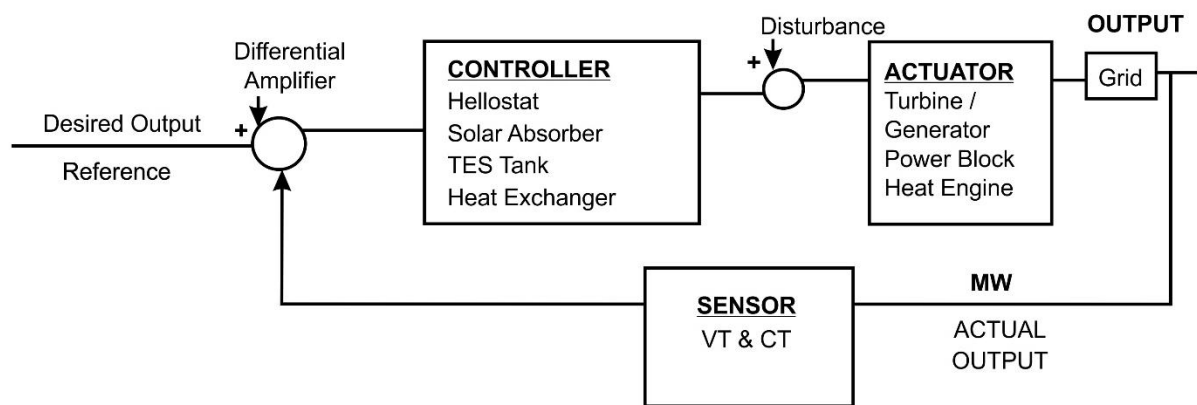


SUNSHINE → HEAT → Pressure → ELECTRICITY →

Figure 35

CST power stations are very dependable!

Central Receiver Tower power plant



LEGEND

TES - Thermal Energy Storage Tanks
 VT - Voltage Transformer
 CT - Current Transformer
 MW - Megawatts

Figure 36

Therefore, the thesis aims to come up with a design template of a Concentrated Solar Thermal Power Plant of the power tower type of size 500 MW.

A heliostat might possess double or single axis for sun tracking. Heat signal or time of day may be the control signal.

In a heliostat, size determines whether it is composed of small mirrors, single big mirror or several mirror module panels. A substrate that backs to constitute a surface that is slightly concave supports the thin glass. For panels of middle to large heliostats, each mirror module is slightly concaved and each segment of the mirror on the heliostat is made to be central toward a focal point. This generates a greater thermal flux density at the point being aimed at.

According to Blanco and Santigosa (2017), every single heliostat, in a central receiver facility has 50-150m² of reflective surface. A typical example is the 186 heliostat each having an area which is reflective of area 54 m² focusing solar flux via a mirror of hyperbolic shape.

The heliostats are made up of numerous mirrors that are independently actuated reflecting the concentrated sunlight toward the effective area of a solar absorber built from ceramic or metal alloys-which can withstand the thermal levels that emanate from in the receiver. Usually, the heliostats are slightly concaved or flat mirrors each having an individual double-axis tracking system.

Methods of Enhancing the overall efficiency of a CRT Power Station

- Enhancing the heliostat mirrors' reflectivity
- Enhancing the solar absorber's absorptivity (make surface black-painted and rough)
- Achieving highest thermal levels for storage causing reduced geographical area to be needed for storage and higher efficiencies
- Modularized and multi-tower designs in order to lower solar flux attenuation from mirrors to the receiver.
- Lowering conductive and convectional losses from the system (e.g. tubes, piping and TES tanks) to the environment i.e. thermal insulation strategies
- Enhancing properties of the heat exchanger (heat emission on one side and heat conductivity on the other side e.g. employing diamond and graphite.

- Enhancing the efficiency of the power block or heat engine i.e. heat to electricity conversion efficiency.
- Before distribution and transmission, to step-up the produced voltages.

Advances in Clean Energy Technology (2023) posits that American Solar Two (upgrade One), the Spanish CESA 1 and TSA and the French THEMIS case studies have enabled knowledge accumulation on power towers. They have allowed enhancement in performance of the power tower and in design. PS10, PS20, Beijing Balading Sierra and Yanqing, adopted water initially as HTF. The Direct Steam Generation development that is currently in its infancy stage as HTF is quite promising for cost reduction and improvement of thermal efficiency by making the heat exchanger unnecessary. Albengoa Solar built the Sevilla plant PS10 in Spain in 2006 with a capacity of 11 MWe. It was followed by the 20 MWe PS20 at the same location (Advances in Clean Energy Technology, 2023).

Wikipedia (2025) points out that Ivanpah Solar Electricity Generating Plant is an example of a solar-gas hybrid plant. It is built in Mojave Desert in California, Nevada state in America. It is built on 3 600 acres (5.76 km²) of land and has an output of 392 MW. Its total cost is \$2.18 billion. It has a tower of 140 m tall and possesses 173 500 heliostat mirrors. It has 3 separate plants. It resulted in carbon dioxide emission reduction of greater than 400 000 tons per year. It was

commissioned in 2013 and there are plans to close this plant in 2026 (Wikipedia, 2025)

Power Technology (2020) posits that Seville Power Plant in Spain is another power tower technology. PS10's output is 11 MW. It is located in the Andalusian countryside in Sanlúcar la Mayor municipality. It has a 115 m Central tower with 624 huge mirrors. It costed 1 200 million Euros. PS20 has an output of 20 MW and has a dual-axis solar tracker. Its central tower is 165 m high.

From Meta AI (2025) : ' Here are some existing Central Receiver Tower Power plants^{1 2}:

- Operational Plants:

- Gemasolar (Spain): 19.9 MW, molten salt storage for 15 hours
- PS10 (Spain): 11 MW, cavity receiver
- PS20 (Spain): 20 MW, cavity receiver
- Beijing Badaling Solar Tower (China): 1.5 MW
- Sierra Sun Tower (USA): 5 MW, decommissioned
- Ivanpah Solar Electric Generating System (USA): 377 MW, three units
- Crescent Dunes Solar Energy Project (USA): 110 MW, molten salt storage for 10 hours
- Khi Solar One (South Africa): 50 MW
- Shouhang Dunhuang II (China): 100 MW, molten salt storage for 6 hours
- Ashalim Plot B (Israel): 121 MW

- Pilot and Demonstration Plants:

- Solar One (USA): 10 MW, decommissioned
- Solar Two (USA): 10 MW, decommissioned
- Jülich Solar Tower (Germany): 1.5 MW
- Themis (France): 2.5 MW, decommissioned
- EURELIOS (Italy): 1 MW, decommissioned
- SUNSHINE (Japan): 1 MW, decommissioned
- CESA-1 (Spain): 1 MW, decommissioned
- SSPS (Spain): 0.5 MW, decommissioned
- TSA (Spain): 1 MW, decommissioned
- MSEE/Cat B (USA): 1 MW, decommissioned
- SPP-5 (Russia): 5 MW, demonstration plant.'

These plants use various technologies, including molten salt storage, direct steam generation, and cavity receivers. Some plants are operational, while others are

decommissioned or under development. Certain plants that were decommissioned had technical and contractual issues.

The project now proceeds to discuss Maintenance methods

Before designing a Central Receiver Tower Power Plant, maintenance techniques require to be brought into consideration to guarantee accessibility of all components is guaranteed in the design and nothing is overlooked.

2.2.6 MAINTENANCE STRATEGIES FOR CSP POWER STATIONS OF THE CENTRAL RECEIVER TOWER TYPE FOR ECONOMIC & EFFICIENT OPERATIONS-A REVIEW

INTRODUCTION

The paper investigates all maintenance strategies that can be possibly employed in the maintenance of A Concentrated Solar Power Stations of the Central Receiver Tower type.

It further posits that there are two main foundational maintenance strategies that can be employed in the maintenance of CSP power plants namely reactive and proactive maintenance strategies. Reactive maintenance is also known as corrective maintenance, fault maintenance or breakdown maintenance. The other name for proactive maintenance is planned maintenance. Preventive maintenance is also a type of proactive maintenance. Proactive maintenance can also be further subdivided into other categories. Among the other categories of proactive maintenance strategies includes periodic maintenance, predetermined maintenance strategies, condition-based maintenance, predictive maintenance and total productive maintenance strategies. Proactive maintenance strategies believe that, 'A stitch in time saves nine!' Timely maintenance interventions are therefore less costly to a power utility as they prevent worse occurrences and downtimes. Predetermined maintenance is whereby the maintenance programme follows the manufacturer's maintenance manual or recommendations rather than the maintenance team's crafted and planned maintenance programme.

Recent maintenance strategies perspectives include Reliability Centered Maintenance, Business Centered Maintenance and Risk Based Maintenance.

The advantages and disadvantages of each and every maintenance strategy was discussed, highlighted and presented. Proactive Maintenance is mainly carried out to prevent unplanned and long total shutdowns in future or to prevent major faults and huge inconveniences to the power utility and end customers caused by sudden and unexpected faults. The paper says that different maintenance strategies that can

be adopted by a power utility have different initial capital costs, different annual costs and different benefits to the utility on the short, medium and long term. The level of maintenance intelligence and sophistication varies with the method adopted. Capital costs increases in proportion to increased intelligence and increased sophistication of the maintenance strategy adopted.

The paper posits that maintenance is not a necessary evil, but essential good which cannot totally be avoided for efficient and effective operations. Planned maintenance ensures that replacement components and maintenance raw materials are available when needed whereas corrective maintenance may be imperative when maintenance raw materials are not available which may take a long time to procure.

MAIN NARRATIVE

A fault is herein defined as any abnormality in the structure and function of any or combination of components or equipment in a machine or plant e.g. a Central Receiver Tower type power plant-be it a solar absorber, tubing, thermal energy storage tanks, boilers, turbine, condenser, cooling tower or generator. Faults slows down, inhibits or prevent production. In order to minimize the adverse effects of faults, maintenance is necessary.

Healthiness and technical functionality of equipment and components of a Central Receiver Power plant is vital, critical and important for superior operations and electricity production. The integrity of certain components may deteriorate due to the passage of operational time and maintenance interventions may be recommended or advisable or just mandatory for continued functioning of the power plant. Maintenance is any work process or activity meant to keep equipment in a working condition or status or restore them to a working or operating condition or status. The formulation of a maintenance strategy considers reliability requirements, cost of downtime and redundancy of assets (Stenstrom et al.,2015). Mechanical resilience, higher thermal withstand in the design of a CRT power plant can reduce the burden and frequency of fault maintenance interventions in the short to medium term.

Maintenance strategies can enhance a Central Receiver Tower's competitiveness as it has a direct influence on costs, quality and flexibility of the power plant (Pinjala et al., 2004). This makes maintenance rise from being a tactical activity to a strategic endeavor. Maintenance can constitute 40% of production costs and therefore it needs

to be considered at the highest organizational level i.e. strategic level. Maintenance is part and parcel of the asset-care corporate strategy. Maintenance costs are likely to rise with the advent and increased deployment of automation, robotics and computer aided devices in CRT power plants. There is room for improvement of profits and productivity if we effectively tap into maintenance capabilities (Pinjala et al., 2004)

Maintenance is a vital and key business area for a Central Receiver Tower power plant. For plant and equipment to remain reliable and safe, it needs to be maintained (Arunraj and Maiti., 2006).

Asset care throughout the life of an equipment is vital for the optimization of production and therefore power utility profits. As mentioned earlier maintenance account for about 40 % of all total costs for a power utility on average and needs to be regarded as the Business Centre and also a profit centre and not a Cost Centre (Thomas.,2010) and Pinjala et al., 2004) [9]. Asset care maintenance strategies has an effect on production optimization, customer satisfaction enhancement and product quality improvement. Average potential for improved production by adopting optimal maintenance strategies is approximated to be 6-8 % (Thomas., 2020).

Use of knowledge of failures and accidents, e.g. failure statistics, failure trends, fault propagation characteristics and fault magnitudes is helpful in choosing the optimal maintenance strategy for a CRT power plant (Arunraj and Maiti., 2006). We need to ensure safety of personnel and members of the public, quality of products and services as well as reduce costs. The maintenance strategy should maximize plant availability, efficiency, effectiveness of equipment, reduce equipment deterioration, ensures safety and environmental protection, minimize total costs of operation.

Product and service quality depends on equipment healthiness and maintenance and product quality. Maintenance is necessary in order to reduce frequencies and consequences and severity of equipment failure. All failure modes have to be known.

Quantified risk  maintenance activities in Risk Based Maintenance.

As the Concentrated Solar Power (CSP) plant's components of the Central Receiver Tower(CRT) type is manufactured, and certified healthy for the purpose of supplying electricity and energy to the grid for the first time i.e. commissioned it is 100% healthy. As it is operated, wear and tear of components begins to set in, develop and advance to the detriment of efficient and effective operation and therefore departs from being in a 100 % healthiness state. The equipment can be said for example to be 80 %, 50% or 0% healthy. At a critical threshold of deterioration e.g. 0 % healthy, it will breakdown and becomes impossible to function and reactive, fault, breakdown or corrective maintenance becomes imperative, compelling and vital in order to restore functionality. During maintenance we are either cleaning, oiling, greasing, repairing or replacing components. Maintenance activities and interventions affects plant operating times, efficiency and effectiveness of operations of the power station. It may also greatly inconvenience customers and end users and therefore affect the bottom-line of a company. Shareholder value may be enhanced or destroyed depending on which maintenance strategy is adopted by a power utility. Maintenance interventions are a compromise between capital costs of deploying sophisticated monitoring equipment and cost of inconveniences caused by unexpected, unplanned and sudden breakdowns. The preparedness and unpreparedness that results therefrom may dictate the type of maintenance adopted. Preparedness implies that when maintenance need to be carried, all the labor, materials, equipment and finance are all available just before and during the maintenance whereas unpreparedness implies that one or more of the above is not available when maintenance needs to be carried out.

The alternative approach is to employ proactive maintenance also called preventative maintenance, periodic maintenance, planned maintenance, annual maintenance, or predetermined maintenance or deploy monitoring equipment and adopt condition based maintenance or predictive maintenance. Total productive maintenance is whereby operators are also involved in the maintenance activities of the Central Receiver Tower power plant.

Maintenance are interventions or strategies meant to restore, repair, replace or bring back deteriorating equipment e.g. turbine, solar absorber back to its ideal operating condition or state. It is a combination of tasks or activities employed to improve equipment healthiness so that it can perform its designated functions effectively as initially commissioned to do (Dhillion, 2002, Duffuaa, 1999). The objective of

maintenance strategies is to preserve and restore equipment and system functionality in a cost effective manner. The plant has to be maintained so that it does not damage the environment-i.e. environmental protection.

A CSP of the Central Receiver Tower has got component equipment that may need maintenance to restore it back into a healthy operational state. Maintenance on non-firm equipment disrupts electricity production capacity because if the equipment is on the critical path along the value chain of the electricity production line, generation may not adequately meet grid demands. This will obviously result in reduced electricity sales. Therefore, maintenance need to be scheduled when demand is lowest in order to minimize monetary losses to the power utility due to lost sales and also to minimize inconveniences to customers and/or end users. For a CRT power plant maintenance may also be scheduled when there is no sunshine i.e, during complete cloud cover conditions or during the night with artificial lighting for the non-firm equipment such as the heat engine and heat exchanger.

As mentioned earlier, there are least two maintenance strategies namely (a) reactive, (also known as corrective, fault or breakdown maintenance strategies) and (b) proactive or preventive maintenance strategies. Preventive or proactive maintenance may be divided into (1) Time based maintenance methods also called periodic maintenance strategies, (2) condition based maintenance strategies and (3) predictive maintenance methods. Then these two maintenance strategies may be subdivided into four maintenance strategies and methods that may be applied to CSP power plants of the Central Receiver Tower type. These methods include (a) condition based maintenance method and (b) predictive maintenance method (c) Time-based or periodic maintenance sometimes assuming annual maintenance strategies (d) total productive maintenance strategies and the most unwanted (d) fault or breakdown maintenance method. Corrective maintenance is also the other name for fault or breakdown maintenance strategy.

Vibrational Analysis

The mechanical healthiness or soundness of machines e.g. electric motors, turbines and generators is normally deduced from vibrational noise and pressure changes

measurement analysis (e.g. piezoelectric material). The characteristics of a lot of vibrations can be sufficiently defined by 3 parameters as follows: -

- (1) Displacement
- (2) Frequency
- (3) Phase

By scrutinizing the pattern traced out on the chart for a vibrating power plant component, the displacement and frequency of its vibration can be deduced. The vibrational displacement is determined and deduced by measuring the distance between the downward and upward maximum excursions. It is often measured in terms of peak to peak (in microns). We can get frequency from counting the number of vibrational cycles e.g. cycles per minute. We can use vibrational noise meters, vibrational noise analyzers or vibration monitors. Broadband vibration and acoustic real-time analysis may be used.

Vibration analysis may also use specifically amplitude, displacement, velocity, acceleration, frequency and phase. Two of the highly important are velocity and acceleration. All three (displacement, velocity and acceleration) can be employed as vibration severity indicators e.g. of the turbine, electric motor or generator. We may employ accelerometers and velocity pickups.

Corrective Maintenance

Corrective maintenance is a maintenance scheme done in so as to locate and rectify the causes of breakdown for an already failed system (Wang et al., 2013). Its other names are reactive maintenance, fault maintenance or breakdown maintenance! The maintenance team intervenes when interruption or restriction of production has actually occurred. They are interventions made after the system is no longer able to operate and production is impossible. Before a fault is rectified, there may be need for fault finding or fault diagnostics in order to ascertain the exact location of the fault.

This maintenance strategy may result in huge levels of downtime, sales losses, sudden and unexpected failure and high inconveniences to customers, the power utility and end users. Maintenance may be vital, critical, compelling or imperative when there are no spare parts or raw materials needed to do the maintenance. Some of these parts and raw materials may require a long lead time to procure resulting in long plant down times i.e. extended non-productive periods. This kind of maintenance is the most ancient and simplest kind of plant maintenance found in power station maintenance. This maintenance strategy will generally be found over the long term to reduce machine availability and offers a lower overall mechanical efficiency for production machinery. Maintenance is only done in response to breakdowns, faults or plant component abnormalities. As mentioned earlier Corrective maintenance is also called fault maintenance, reactive maintenance or breakdown maintenance. It is the most logical type of maintenance to any layman. Reactive maintenance can be implemented on any part of the Central Receiver Tower power plant components e.g. heliostat, solar absorber, pipework, Thermal Energy Storage tanks, heat exchanger, turbine, generator, condenser, cooling tower, control room etc.

Scheduled Maintenance

This is the initial step in the approach to modern maintenance strategies. It involves joint advance discussions between production department and the maintenance department so that items considered of use by maintenance staff to need attention can be scheduled to be available for repairs. Through this approach the ‘where’ and the ‘when’ of the maintenance programme can be approximately fixed and the most efficient use made of any idle time. The most convenient time to production and the maintenance team is thus struck in order to schedule maintenance.

Planned Maintenance

This strategy is one step ahead of scheduled maintenance which decides not only the, ‘when,’ and the ‘where’, of maintenance, but also answers to the questions ‘what’ and ‘by whom’.

Preventive Maintenance

This maintenance strategy answers the questions, 'where?', 'when', 'what', 'by whom?' and, 'why?' It incorporates the policy of replacement, upkeep and modification rather than repair and includes inspections of the plant so as to diagnose the trouble, if any, and to plan the needs and requirements of maintenance. An analysis of earlier maintenance schedules, maintenance history, downtime or breakdown hours etc is necessary in order to introduce preventive maintenance.

The execution of maintenance activities and tasks precedes failure events and is done prior to breakdown of equipment. It minimizes downtime and failure costs as well as sales losses as maintenance is scheduled at most convenient times. Preventive maintenance is more expensive in the short term but more cost effective than corrective maintenance in the long term. In preventive maintenance, one employs inspections and undertakes maintenance regardless of whether such maintenance is necessary or not. Preventive maintenance does not make it imperative to have monitoring equipment which is required by condition-based maintenance or predictive maintenance and hence require less capital investment in training and technology.

After a fault has occurred, there may be fault propagation where one fault causes another fault on another equipment or system since equipment is interdependent and interrelated (Wang et al., 2013). The ratio of Preventive maintenance to corrective maintenance should ideally be 80/20 (Stenstrom et.al., 2015).

Preventive maintenance maybe done on any of the components of the Central Receiver Tower power plant.

The objectives of systematic preventive maintenance are: -

- (1) To lengthen the working life of the equipment and ensure optimum availability.
- (2) Preserve the value of equipment by minimizing the wear and tear
- (3) Investment safeguarding
- (4) To ensure safety of personnel and equipment
- (5) To keep productive assets in a health and working state.

Condition Based Maintenance(CBM) Method

CBM is a maintenance philosophy that executes maintenance tasks and activities in response to information collected through real-time condition monitoring processes or visual or audible senses. Spotting upcoming failures is vital, critical and important for effective maintenance planning and maintenance scheduling. Condition surveillance equipment may provide historical and real-time data from online instruments and or systems about equipment health status or process dynamics to local or remote monitors. The idea being to transition from problem solving to problem avoidance or prevention. This is only possible if surveillance or monitoring equipment is deployed although visual inspections may save the purpose. It is a strategy for maintaining plant components that relies on real-time surveillance of equipment condition in order to detect incipient or upcoming faults. Observed monitoring data dictates the type and extent of maintenance to be done. There is need to optimize maintenance and performance diagnostic tools need to be employed which may add to the increase in capital costs of the plant. This makes condition based maintenance initially costlier than breakdown maintenance, but may be cheaper on the long term.

This maintenance strategy may be adopted if the power utility installs condition monitoring equipment such as harmonic signature machines, accelerometers for measuring changes in vibrational dynamics of equipment which indicates development of a fault. Maintenance done when the condition of a part of a CSP power plant indicates need for maintenance.

CBM should only be applied where condition monitoring equipment and techniques are available in a cost-effective manner. CBM utilizes condition thresholds to determine when maintenance is to be done. Condition Based maintenance utilizes collected data during monitoring to carry out maintenance at the exact moment in time before a critical breakdown happens. Visual inspection can be done on any component of the CRT power plant although special condition monitoring equipment is recommended for the storage tanks, turbine and generator such as accelerometers, harmonic signature equipment, vibration analyzers.

Predictive maintenance

This strategy is adopted when a power utility utilizes condition monitoring data with forecasting methods. Sensing technology proliferation and Computer or microprocessor-based instrumentation developments have provided a means or capacity for monitoring equipment or component healthiness. For example, changes in vibration of e.g. a turbine, energy storage tanks may continue to increase in the magnitude of the changes observed using accelerometers. Statistical data or Forecasting methods such as Time Series Linear Regression may be used to determine when fault or breakdown is going to occur or when maintenance can optimally be done. Maintenance is then scheduled at the most convenient period resulting in reduces sales losses and minimum disruption to customers. The maintenance engineer of the concerned CSP then decides at what point is necessary to schedule maintenance proactively, economically and conveniently.

Predictive maintenance strategies rely on e.g. machine learning to dynamically determine when equipment is O.K. and when it needs maintenance. It seeks for cumulative patterns across all sensors and transducers and determines one multivariate prediction model. It predicts when in future maintenance is to be done.

Extra tools like machine learning has also facilitated predictive maintenance.

Artificial Intelligence(AI) and Predictive Maintenance

Artificial intelligence is the embedding or implanting of human intelligence, any or all of the five senses and decision making capabilities in machines especially computer systems. It is the use of the theory and practice of computers that are capable of performing duties and tasks that are normally carried out by human beings' intelligence for example sound recognition, machine vision, decision making and interpretation of data. Huge amounts of labelled data are used for training, analyzing the data for patterns and correlations in order to predict future states.

In order to write and train machine learning algorithms, specialized software and hardware are needed. Languages normally associated with AI include C++, Java, Python and R. AI programming concentrates on learning, reasoning, self-correction and creativity.

AI has capacity to detect condition of an equipment and permits it to estimate or predict when maintenance can be optimally performed.

According to (Industlabs report., 2023). Artificial Intelligence used in Predictive maintenance allows power utilities to depart from a set schedule and be responsive to the needs of each piece of plant equipment. AI makes predictive maintenance more cost effective and efficient.

An AI system has capacity to recognize patterns and trends of developing defects or imperfections after training with a small number of images.

AI robots can also be used to do part or all of the maintenance activities thus saving maintenance labor costs.

AI can also adapt to a fast changing market environment by use of algorithms that makes supply chains optimal, efficient and effective. Changes can be anticipated in the market and permits management to move to a strategic mindset from reactionary mindset. Artificial intelligence allows equipment information to be available all the times.

Internet of things (IoT) based predictive maintenance solutions can diagnose defects and do a root-cause analysis.

Periodic Maintenance

This maintenance strategy requires maintenance to be carried on every equipment after the same time interval period e.g. Annual maintenance plans. For example, in the Zimbabwean power utility every 33/11 Kv distribution transformer needs to be maintained annually. Turbines and generators in the CSP of the Central Tower type may also be maintained annually at convenient times e.g. during weekends and Holidays when industry is closed for example,

The problem with periodic maintenance such as annual maintenance is that other studies showed that 80 % of such maintenance may not be necessary leading to unnecessary costs and production disruptions and why condition based maintenance may be prudent.

Techniques such as vibration analysis and echostic measurements can give a clue to the healthiness of an equipment. There may be need for trend profiling in order to predict, plan and schedule optimal maintenance times.

Fault Maintenance

Fault maintenance is also sometimes called reactive, corrective or breakdown maintenance. Maintenance may only be carried out if there is a CSP component which is faulty or has broken down It is the simplest type of maintenance strategy. Unfortunately, this breakdown may occur when demand is highest leading to massive economic losses to the power utility in terms of lost sales and great inconveniences to the utility customers and end users. Raw materials and equipment for maintenance may not be in stores or available leading to long outage times. Power utilities with serious financial problems may resort to this type of maintenance.

Maintenance activities may further be classified as follows: -

- Reliability-centered maintenance strategies
- Business-centered maintenance strategies
- Risk-based maintenance strategies

- Total productive maintenance
- Total production maintenance

Reliability Centered Maintenance

Reliability Centered Maintenance(RCM) is a maintenance philosophy which ensures or guarantees that maintenance activities are executed in such a manner as to guarantee safety, efficiency, cost effectiveness and reliability (Inspectioneering report., 2017). It emphasizes reliability and safety capabilities of equipment at minimum cost (Stenstrom et.al., 2015). RCM introduces new strategic framework for ensuring that every asset continues to operate, function and work in the way operators and users want it to perform (Moubray., 1997). It seeks for a strategic framework that incorporates new advances in technology into a coherent and integrated pattern, so that sensible evaluation and application of them is likely to be of most value to the plant's operations and production functionality (Moubray., 1997). The aim of RCM is to ensure that inspections and maintenance activities are focused on improving the reliability and safety of equipment.

According to (Barges., 2016), Maintenance perspectives have been transformed during the last 30 years. Preventive maintenance assumes a cause-effect linear relationship between scheduled maintenance and power plant operating reliability. It assumes that since mechanical components wear out as operating time increases,

Equipment Reliability is inversely proportional to operating age.

Frequent maintenance implies more increased protection against probability of breakdown. This is not the case as frequent scheduled maintenance can actually cause increased failure rates. The purpose of preventive maintenance is not to eliminate failure altogether but to mitigate consequences of failure. Failure consequences differ depending on where and how the equipment is installed and operated.

The 7 Reliability Centered Maintenance Questions (Barges., 2016).

1. What are the equipment's functions?
2. Within what conditions could the equipment become faulty?
3. What are the reasons and drivers of equipment to failure?
4. What results occur if the equipment experience failure?
5. Is it material or significant if the equipment faults?
6. Could anything be done to avoid equipment failure?
7. What needs to be done if the failure is unavoidable?

In RCM we consider the characteristics of failure of the equipment under consideration, risks and costs involved. RCM brings higher environmental and safety integrity, enhanced performance of operations, cost effectiveness and better teamwork i.e. social cohesion in work ecosystems (Barges., 2016).

Business Centered Maintenance(BCM)

This philosophy or maintenance perspective and strategy takes maintenance as the Business centre! It does not view maintenance as a Cost Centre, but a profit centre. BCM is a concept and attitude in maintenance philosophy that aims at the process of continuous improvement in maintenance activities, equipment performance and condition which thrives to improve employee safety, output quality, operations efficiency and overall equipment effectiveness (Infraspeak report.,2020). BCM is tuned to the hype and vibe of instability and change caused by mutating technology and world competition.

According to (Infraspeak report.,2020), the 12 crucial points to Business Centered Maintenance are: -

1. Organizational management (Infraspeak report.,2020).
2. Reliability and Effectiveness
3. Budgets and Costs
4. Management of information systems and planning
5. Safety, quality, environment

6. Internal and Foreign Relations
7. Personnel Management
8. Supplies and Logistics
9. Internal organization (Functional structures, resources, outsourcing contracts)
10. Continuous improvement
11. Risk analysis
12. Compliance

RISK BASED MAINTENANCE (RBM)

RBM is a maintenance philosophy and perspective that emphasizes, prioritizes and deploys maintenance resources towards that equipment that bear and has the most risk if failure occurs e.g. a solar absorber and heat engine in the case of a Central Receiver Tower power plant (Rockwell Automation report., 2020). It's a methodology for ascertaining that maintenance resources are utilized as most economical as possible (labor, materials, equipment) It optimizes maintenance in order to reduce risk of failure to the lowest level. Risk Based Maintenance ensures inspection of high risk parts having higher thoroughness and frequency in order to achieve tolerable risk criteria. Its aim is to assist in decision making and maintenance planning in order to diminish the chances of breakdown of equipment and the adverse results of such breakdown or fault. This needs Risk analysis. This ensures product quality, plant safety and reduces operational costs.

Risk based Management is based or premised on 2 major phases: -

1. Assessment of risk
2. Use of risk in carrying out maintenance planning

The category or kind and frequency of maintenance are given priority and pivoted on failure risk (Rockwell Automation report., 2020). Equipment with the highest risk and highest consequence of failure are maintained and monitored more frequently. Assets or equipment with minimal or low risk if they fail are subjected to less maintenance interventions. This ensures that the total risk of failure is minimized throughout the power plant and in the most economical way (Rockwell Automation report., 2020).

CSP Power Plant of the CRT Type

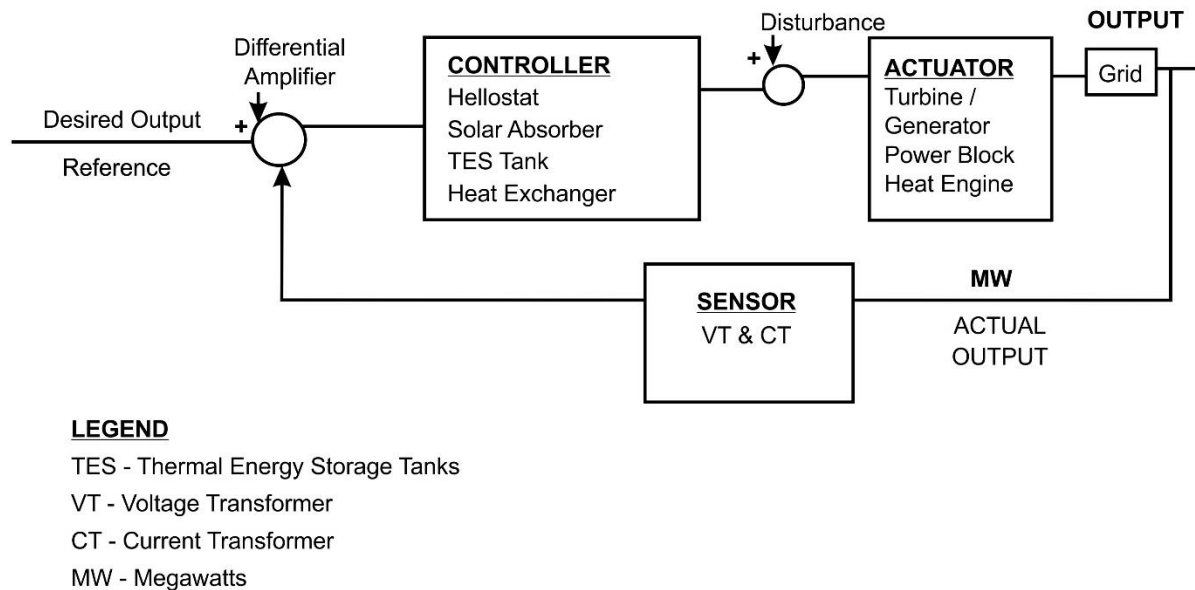


Figure 37

Components to be maintained include

- The heliostat assembly
- Solar absorber
- Thermal Energy Storage Tank
- Heat Exchanger
- Pipes & pipework
- Turbine
- Generator
- Condenser
- Cooling tower
- Control room

Both reactive and proactive maintenance strategies may be employed in the maintenance of all or any of the above components of a Central Receiver Tower power plant, but some are better, more economical and better sales-promoting than others.

Because direct generation is paralleled with the thermal Energy storage tank, the TES tanks can be maintained whilst generation is taking place. The heliostat can be maintained during complete cloud cover days for example.

HELIOSTAT MAINTENANCE

A heliostat is an assemblage of mirrors on a support which moves so that throughout the day the sun's rays will always be reflected on a stationary and fixed solar absorber. The mirrors intercept and reflect the sun's rays onto a solar receiver or solar absorber. The mirrors should have very high reflectivity and very low absorptivity for efficient and effective functionality.

Since there will be numerous heliostats (1000 to 2000 heliostats) on a single plant, the heliostats can be maintained one at a time without loss of total production i.e. while production goes on at a reduced level! It is recommended to maintain heliostats during periods of complete cloud cover or during the night using artificial lighting. The heliostats need to be cleaned periodically to remove dirt or dust in order to enhance reflectivity. The mirrors and the mirror supports need regular maintenance. The rotating mirror supports need to be greased periodically. Painting of mirror supports to eliminate rust may also be necessary. Wind loads may present sheer stresses and tensile forces on the heliostat supports which may bend or break the heliostat supports. In this case the support members may need complete replacement or repair.

The mirrors may also break or crack and may also need complete replacement.

Solar Absorber Maintenance

A solar absorber is a CRT component where solar concentration occurs from heliostats. Sun's rays from a large area of mirrors is concentrated on the smaller area

on the solar absorber. The other name for a solar absorber is solar receiver. The concentration function need to be done efficiently and effectively.

In a mono-tower Central receiver Tower there is only one solar absorber for the whole power station, a total shutdown is required in order to maintain the solar absorber or central receiver. The solar absorber may also be maintained during the night when there is no light energy impinging on it. There may be leaks on the receiver due to yielding to thermal stresses. The pyrometers in the solar absorber may need maintenance. The pyrometers in the solar absorber may help to monitor temperatures therein. Thermal yield may occur on the solar absorbers due to excessively high temperatures or insufficient designs! Material sciences need to be undertaken in choosing materials for the solar absorber.

In a multi-tower and therefore multi-solar absorber power plant, one solar absorber maybe maintained whilst electricity production goes on

Heat Energy Storage Tank Maintenance

Heat Energy Storage Tanks are tanks that are utilized to temporarily store hot thermal transfer fluid such as molten salt (e.g. a mixture of sodium nitrate and potassium nitrate). The tanks are normally made of steel or nickel alloys. The melting point of the materials used to manufacture the tanks must have a melting point above the heat transfer fluid's normal functioning thermal levels (565°C upto 1000 °C).

Direct generation can be done whilst the thermal energy storage tank is being maintained. This means energy production is possible during the day when thermal energy storage tanks are being maintained. The thermal energy storage tanks can develop leaks! This means that energy loss through the thermal energy transfer fluid leaving the storage tank into the environment will be occurring. Welding maybe necessary to eliminate leakage holes on the tanks. The tanks may also need repainting to eliminate chances of corrosion. The level, pressure sensors in the tank and pyrometers may also need maintenance.

Maintenance of the Thermal Energy Exchanger

A thermal energy exchanger assists in the conveyance or passing of thermal energy from the heat transfer fluid (molten salt) from a solar absorber or from the storage tanks to the working fluid(steam) which drives the heat engine or power block. A heat exchanger is supposed to be made of a very good conductor of heat e.g. graphite or diamond. Thermal conductivity analysis of materials and metals need to be done in order to select materials for constructing heat exchangers.

Since there is only one heat exchanger per power station, a total shutdown of the power station would be needed so as to maintain the heat exchanger.

Pipes & Pipework Maintenance

A total shutdown will be required for pipework maintenance. The electric motors which determines the flowrate in pipes may also need maintenance. The pipework may also develop leakages and welding may be necessary! The tubes may also need repainting to prevent corrosion. General cleaning of the pipes may also be required. The pipework's thermal insulation may also need to be maintained or repaired.

Turbine Maintenance

A turbine is a device or gadget which converts pressure of moving air or water (i.e. any moving fluid) e.g. steam pressure into kinetic energy of rotation. It is also alternatively known as a prime mover. The turbine will be coupled to a generator using mechanical bolts such that its rotational will directly be translated into the generator's rotor's rotation thereby generating electricity.

A total shutdown will be required to maintain or repair the turbine set.

Generator Maintenance

A generator is some machine which transforms the energy of rotation in the form of kinetic into electrical energy. It comprises of a field of magnetic and rotor windings.

Some total shutdown will be needed so as to maintain the generator.

All equipment which require total shutdown have to be maintained simultaneously for example solar absorber, pipework, heat exchanger, turbine, generator and condenser.

Maintenance of the Condenser

A total shutdown will be required

Maintenance of the Cooling Tower

A total shutdown maybe required.

Conclusion

The paper recommends predictive maintenance as the best maintenance strategy followed by condition based method, followed by predictive maintenance .and negatively recommends fault maintenance strategy for CSPs Of the Central Tower type.

Solar absorber, the heat exchanger and the power block carry the highest consequences and risk of failure and need more monitoring technology under risk based maintenance. The thermal energy storage tanks also need to be monitored closely as its failure has great consequence for night generation.

The paper identified the following equipment that needs maintenance on the CRT power plant: -

- Heliostat assembly
- Solar absorber
- Pipes from the solar absorber to the energy storage tanks and pipes from the solar absorber to the heat exchanger.
- Heat Storage Tanks

- Pipes from the Heat tanks to the thermal energy exchanger
- Heat exchanger
- Pipes from the thermal energy exchanger to the power block/heat engine
- Nozzles
- Heat engine/power block
- Conductors and busbars from the generator to the 11 Kv side of the 11/330 KV transformers
- The condenser
- Pipes from the heat engine to the condenser
- Pipes from the condenser to the solar absorber

Preventive maintenance to corrective maintenance must ideally be in the ratio 80/20 where both types of maintenance are adopted [13]

The project now proceeds to discuss the design of the heliostat Solar Field.

The following Chapters addresses the computations and design of the numerous parts of a 500 MW Solar Power Tower power plant alternatively known as the Central Receiver Tower Power Plant starting with the design of the Heliostat Solar Field.

CHAPTER 3-METHODOLOGY

The methodology tries to address the research gap identified in literature in that there is no template or clearly articulated methodology for manual design of a Central Receiver Tower power plant components

Before we start to design the components of the Central Receiver tower power plant we need to do an environmental Impact Assessment for the plant.

Environmental Impact Assessment for the Central Receiver Tower Power Plant

- (1) The heat from the power plant e.g. concentrated heat from heliostat mirrors may kill flying birds
- (2) Large tracks of land for farming and mining will be taken by the plant
- (3) Spillage of molten salt during leaking faults may pollute the environment
- (4) Risks of thermal, mechanical and electrical accidents to operating staff

Technical Analysis

The day and night, clear sky and cloud conditions fluctuating weather conditions, causes solar generation to introduce grid instability without thermal energy storage of hybridization. For parallel steam path hybridization, there is need for thermal matching. In parallel steam path and parallel generation, there is need for phasing and synchronization. The average thermal energy storage fluid temperature in the receiver and heat exchanger must be 565 °C for proper functioning of the power plant. The proposed powder station should comply with ASME and IEC standards.

ASME PSD1 Standard says, ' New plants and facilities with potential for significant environmental, safety and health hazards to worker and or public may not be built unless costs to license, design and construct can be significantly reduced, while ensuring safety and health to the worker, the public and environment'.

Economic Analysis

The proposed CRT power plant is very expensive and has high capital and maintenance costs. Funding for the project has to be done by borrowing money from

banks like World Bank, African Development Bank or IMF who are now tight on cash. The other option for the Zimbabwe Electricity Supply to raise money for the proposed power station needed to supplement bank loans is to float Bonds.

Benefits of Supply and Demand Matching

- (1) Electricity adequacy
- (2) Improved standard of living in the country.

The project is practically feasible since it has been operated in other countries although in certain countries there were technical challenges leading to plant closure.

The thesis now proceeds to design the heliostat solar field.

3.1 Design of a Heliostat Solar field for a 500 MW Power Tower Power Plant Type

INTRODUCTION

The section analyzes literature on the design of solar fields and proceeds to do calculations of the size of the solar field required to generate 500 MW using a Central Receiver Tower power plant. Solar intensity levels for Kadoma, which is the proposed site are obtained from the internet. This solar intensity level together with allowances for losses such as shading and blocking is used to size the field which will be radial staggered. The section highlights that mirror reflectivity, atmospheric attenuation, spillage, blocking, shading and cosine losses are the major energy losses between the field and the solar absorber. A 96 % mirror reflectivity and an overall 20 % plant efficiency was assumed. The section posits that multi-tower designs increases plant efficiency and therefore a single tower, double tower and 5 tower fields with a common power block were calculated and sized

In conclusions, areas for future research were recommended.

MAIN NARRATIVE

There is world pressure to scale down on fossils fuels and Concentrated Solar power of which the Central Receiver Tower power plant is one is a viable option. This power station requires a heliostat solar field. The problem Statement is (1) how to design a heliostat field for a 500 MW solar power plant in order to replace fossil fuels in Zimbabwe. The research questions are (a) how big is the solar field for a Central Receiver Tower power plant if a single tower is adopted? (b) what is the size of the solar field if a double tower is constructed? (c) what are the dimensions if a 5 tower is preferred?

Objectives

- (a) To calculate the solar field's dimensions for a single tower
- (b) To size the field for a double tower and
- (c) To dimension the field for a 5 tower plant

According to Zhao and Jiang (2023), a heliostat is a mirror that can rotate horizontally and vertically so as to adjust the solar flux's angle of reflection (the sun's insolation i.e. sunlight angle of reflection). A heliostat field is a very important

component of the Central Receiver Tower power station when considering initial installation costs (50% of total cost) and losses (40%). Hoftschmidt and Kaufhold (2012) posits that a heliostat is an assemblage of mirrors designed to trap solar flux from the sun and reflect it onto a solar absorber on top of a tower throughout the day as the sun moves from East to West. According to Pfahl and Coventry et al. (2017), the mirrors are slightly concave and can turn in two degrees of freedom. High temperatures at the receiver are facilitated by heliostats having a large surface area reflecting solar radiation onto a smaller area of the solar absorber (Collado and Guallar (2012). Bern et al. (2019), says that higher absorber temperatures facilitates higher power block efficiency. A heliostat may comprise of large mirror modules for example 120 m² or several smaller mirrors.

According to Hoftschmidt and Kaufhold (2012), a substrate on the mirrors results from a slightly concave mirror surface arrangement.

The assemblage of mirrors requires canting facing toward the focal point on the solar absorber's body. A bigger solar insolation density is thus attained on the solar absorber.

Hoftschmidt and Kaufhold (2012) posits that concentration factors ranging from 300 to 1 500 which results in temperatures of between 150 °C and 1000 °C are attained as a result.

Frequently the reflecting area that will be fixed onto a given or specified heliostat unit ranges between 50m² and 150 m². The function of the heliostat field is to trap and reflect maximum solar flux and focus the solar radiation onto a stationary solar absorber. It is crucial to have high reflectivity of mirrors and must be free from dust so as to achieve higher efficiencies.

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The heliostat solar field constitutes 50% of the total investment costs of a power plant and 40% of the overall energy costs (Pfahl and Coventry.,2017). Since 40 to 50 % of the expenses of installation of a CRT power station is taken by the field of heliostats, therefore its design is vital in order to ensure cost effectiveness in the overall design.

Hu et al (2018) posits that heliostat losses consists of blocking, shading, cosine losses, spillage, reflection losses and atmospheric attenuation losses. Hu et al (2018) further says that cosine losses and astigmatism involving heliostats contribute to lower efficiencies in Central Receiver Tower power plants. According Zhao and Jiang (2023) cosine loss is the loss of received sun's flux energy which results from the valid point that the sunlight's direction of incidence is not parallel to the direction of the normal of the mirror. Improvements in the heliostat mirror manufacturing together with solar absorber aiming and tracking may lower some of these losses which are due to error.

According to Hu et al (2018), cosine loss is the energy loss which results from oblique incidence of the solar radiation onto the heliostat mirror surface. The key variables of a heliostat field are optical quality, tracking accuracy and minimization of spillage or pointing accuracy. A big malfunction exists if the heliostat misses the target and the problems normally are control hardware, communication or defective actuators.

According to Blanco and Santigosa (2017) the reflectance of heliostat mirrors as of 2010 was 94% and was targeted to be 95-96% in the 2020-2030 decade. The mirrors' life expectancies are projected to be between 10 to 30 years as highlighted by Blanco and Santigosa (2017).

The mirrors must possess light weight, corrosive resistance, have high reflectance and must be resistant to weather.

They must also have anti-soiling properties. This diminishes water consumption. Heliostat fields may consist of between 1 000 to 100 000 heliostats in large scale fields (Collado and Guallar.,2012).

The following sizes of heliostats exist, for smaller heliostats 2m^2 , 8m^2 , 15m^2 , for average sizes 48.5m^2 and for larger sizes 96m^2 , 115.7m^2 , 140m^2 and 178.5m^2 . Packed fields have greater shading and blocking while less packed fields have less shading and blocking.

Inaccurate heliostat orientation and spillage are major factors to consider in the design of heliostat fields for the Central Receiver Tower power plants (Collado and Guallar.,2012).

Concerning heliostats, a tracking accuracy of less or equal to 1 milli radian must be aimed for. The following are generally the causes of heliostat aiming or focusing errors Collado and Guallar (2012): -

- Angular offset of the tracking mechanism
- The tracking axis not being perpendicular
- Atmospheric refraction
- Gravity causing bending
- The levelling of the heliostat pedals not being perfect
- The pivot point being offset
- Mismatch between surveying, solar and civil coordinates system concerning the site and programming errors
- The heliostat's back drive
- Slow encoder resolution
- Installation errors (azimuth and elevation reference angle, pedestal tilt, non-levelling terrain) Collado and Guallar (2012).

Errors which are caused by Mirrors

- The deformation caused by wind loading

Automatic Heliostat Track Alignment Method is still the state of the art calibration method employed by most commercial CRT plants (Collado and Guallar.,2012)

The solar field's efficiency determines the performance of the CRT power plant. Aerosols, humidity, tracking technology employed and the solar field layout has consequences on the total solar flux reaching the receiver (Cruz and Redondo (2017)

The heliostat needs to have 2 degrees of freedom. It requires to turn in the azimuth direction as well as in the tilt direction. The actuators are normally hydraulic actuators or motors. The computers programmed with astronomical equations gives signals from inputted date, time, latitude and longitude information.

Heliostat Control

According to Berenguel (2004) heliostat control(HelioControl) can be done with the assistance of B/W CCD cameras in order to correct for beam deviations of the

centroid from the desired aim point. Berenguel et al ((2004) posits that the system mimics the method where operators carry out the correction of offset, i.e by observing an image on a screen of a television got from a camera of the typically B/W CCD type fixedly positioned in the field and attempting to centre the reflected sun's image centroid with the centre of the target. So as to have the thermal level spread that are needed, temperature distribution and flux, the aim-point strategy is used during operation.

The duty of eliminating after identifying heliostat offset errors is done by operators. Pointing accuracy that is high is needed so as to focus the highest amount of solar flux (Chiesi et.al., 2017)

Chiesi et al (2017), alludes that the image of the sun that is reflected by each heliostat onto a target of a receiver is captured by the CCD camera. Those images are used to give feedback information thereby permitting the calculation of the distance between sunbeam centroid and the target centre and the angle is employed for adjustment needs.

Ashley et al (2017), says that inappropriate aiming strategies may damage absorber components.

Ashley et al. (2017) further highlights that one may use the integer linear programming technique in order to optimize the aiming strategy. The life span is determined by temperature distribution along the receiver's surface. Ashley et al (2017) highlights that the most commonly used aiming strategy assumes that the mirror heliostats in the field aim at the center of the receiver.

This results in large flux distribution at the centre of the receiver and huge thermal flux gradients at the edge of the receiver. Spillage losses results from different aim points different from the centre but diminishes peak flux at the centre. This alters the spillage efficiency, slant range, heat distribution across the surface and cosine efficiency.

According to Hoffschmidt and Kaufhold (2012), the solar field's working thermal levels range is dependent on that Heat Transfer Fluid that is used.

The high specific heat capacities and high boiling point make molten salt i.e. potassium nitrate and sodium nitrate suitable for use as heat transfer fluids. The field of the heliostat is the first and costliest part of the Power Tower power station. A mirror normally plane mirror is installed on a heliostat and it reflects sunlight onto a

stationary and fixed solar absorber from sunrise to sunset. The sun-heliostat-absorber angle is bisected by the mirror normal. The reflection angle is always equal to the incidence angle. Modern computers manipulate the actuators. The details of date, time, latitude and longitude is fed into astronomical software in the computer. The astronomical software calculates the sun vector. The absorber vector is constant and known. Using these two vectors i.e. the receiver vector and the sun vector, the mirror normal vector is calculated by the computer. The heliostat is then moved according to the mirror normal vector using actuators.

The heliostats deflect and refocuses sunlight from a huge surface area of mirrors to a small surface area of the solar absorber. Two degrees of freedom are required by the heliostats to turn azimuthally and tilt-wise i.e, altitude.

The heliostat controls are based on heat signals or time of day. A heliostat may be formed from several tiny mirrors or a single large mirror. The thin glass is supported by substrate backing.

A larger flux density results from canting the heliostat towards the focal point.

Ceramic or metal solar absorbers are normally used. The heliostats are made from many independently actuated mirrors.

OPTIMIZATION OF FLUX DISTRIBUTION IN SOLAR TOWER PLANTS

According to Blanco and Santigosa (2017), A solar thermal power tower station comprises of mirrors' (heliostats') field configured round a tower that will be having a receiver at its top.

In the process of tracking the sun, the mirrors on the heliostat focus the sunlight onto the solar absorber.

The field could comprise of a huge number of heliostats (greater than 900 in commercial plants of modern day each of which are controlled independently,' according to Blanco and Santigosa (2017). Muhammad et al (2023) posits that among other heliostat field configurations the radial staggered and Fetmat's spiral distribution are known to exist.

Blanco and Santigosa (2017) posits that solar thermal power towers function at temperatures that are higher e.g. at the solar absorber (700 °C-800 °C) using receivers made from metal and in excess of 1000 °C using receivers of the ceramic type.

Higher temperatures permit smaller and less expensive heat energy storage tanks and higher power production.

Average temperature of 700 °C in volumetric solar absorbers on top of a tower of approximate height 86m. Tubular receivers and volumetric receivers are two types of receivers available on the market.

The Central Receiver Tower power stations nowadays have achieved efficiencies ranging from 30% to 40%.

Heliostats comprise of the mounting and tracking system, control system and effective area.

Long time ago heliostats were 4.5m²(2.4m x 1.84m) but now are upto 7.22m² which are easily transportable by ship and allows flexibility to suppliers.

According to Pidaparathi et. al (2015) heliostats in Central Receiver Tower power plants range in sizes from 1.14 m² to 150m². Theoretically, the least cost of electric energy is obtained by employing 36m² dimensioned heliostat. Generally, the least cost is got by employing the range 20-40m² with AR more than 1. Pidaparathi et. al (2015) says that the solar to thermal efficiency involving external cylinder receivers was set to 88 %.

Pidaparathi et al. (2015) posits that heliostats are classified into 3 basic classes namely small (1 to 20m²), average (20-60m²) and huge heliostats(60-150m²)

Heliostats take approximately 50% of the installation cost of the whole power plant which implies that great effort has to be put in its design.

Blanco and Santigosa (2017) posits that in light of a ninety-four percent as the beginning reference in 2010, the targeted reflectance level in a decade 2020 to 2030

for silvered reflectors is pegged at ninety-five percent to ninety-six percent as stipulated in the European Commission's materials road map that was published.

The economic target is to attain a 25 % reduction in the cost of the reflector in comparison to 2010 values. Blanco and Santigosa (2017) highlights that considering reflectors, numerous priorities in research can be identified: -

(a)develop durable and light-weight reflective surfaces.

(b)improve anti-soiling capabilities within reflectors to reduce water consumption

©increase the reflectance of glass-based reflectors by enhancing the transmission of glass.'

Blanco and Santigosa (2017) alleges that elevating or upscaling of the solar mirror's reflectance allows solar field size reduction whilst keeping the electrical energy output and investment expenses for the collectors or heliostats constant

Increasing thermal and optical efficiency while operating at the liked temperature facilitates achievement of collector efficiency. System efficiency can be enhanced by (1) increasing thermodynamic conversion e.g. heat into electricity and (2) decreasing parasitic losses and heat losses.

Blanco and Santigosa (2017) emphasizes that the most useful and portal among all of these techniques for reduction of costs is the solar concentration concept.

Anti-soiling coatings

According to Blanco and Santigosa (2017), a lot of attention is currently being focused on anti-soiling coatings by researchers, reflector manufacturers and plant developers because of their capacity to reduce soil accumulation on the reflector surface. This results in reduced cleaning activities and therefore water consumption by the CRT plants. Dust particles are prevented from settling or sticking on mirror surfaces as they have a devastating effect on the optical properties of the mirrors. In addition, the reflector and coatings combination must be reliable and durable when exposed to high temperatures, higher than normal exposure to ultraviolet (U.V.)

visible and infrared radiation as well as sandstorms. They must withstand any cleaning procedure. According to Blanco and Santigosa (2017), materials used for hydrophobic coatings are mainly fluoropolymers.

HIGH-PERFORMANCE MIRROR MATERIALS

According to Blanco and Santigosa (2017), 'Raising the reflectance of the solar mirror permits a reduction in the solar field size while maintaining the electricity output and the investment cost for collectors or heliostats.

Tiny enhancements in reflectance of 0.5 ppt can achieve huge effects on electricity production. High reflectance could be attained using silver as the surface for reflection together with a thin coating which is transparent.

Thin glasses available commercially of around 1mm glass thickness attain about 95.7% solar weighted hemispherical reflectance.

Blanco and Santigosa (2017) posits that, 'optical designs can help to achieve higher performances and better cost-effectiveness factors.' This can be insinuated by the solar tracking facility of the heliostats.

According to Blanco and Santigosa (2017), the present concern possessing solar collector designers is being able to facilitate delivering electrical and thermal energy at lowest possible cost. In order to achieve this milestone, several options can be pursued amongst them (1) minimizing operations and maintenance costs (2) minimizing system costs (3) minimizing collector costs (4) enhancing system efficiency and (5) improving collector efficiency.

Improving thermal and optical efficiencies at the needed operational thermal levels facilitates attainment of collector efficiency. System efficiency could be improved for example by (1) improving thermodynamic conversion efficiency e.g. thermal energy to electric power (2) Minimizing thermal losses encompassing parasitic losses e.g. pumping power.

Mass production causes reduction in collector costs. Easier manufacturing technologies, new designs and new materials facilitates minimization of weight and other mechanical variables.

Reduction in heat transfer fluid and number of components may cause a reduction in system costs. New operating strategies and employing new control results in reduction of operating and maintenance costs. The most useful handle within all the above efforts is the concept of solar concentration

CONCENTRATION

Blanco and Santigosa (2017) posits that $2\Theta^0$ is the collector's acceptance angle which relates inversely to the concentration. There exists a limit for the concentration that can be achieved per given half acceptance angle Θ . For linear optics is given by: -

$$C_{\max} = A_{\text{apperture}} / A_{\text{receiver}} = \eta / \sin \Theta \quad \text{Equation 3.1}$$

At the receiver aperture, the refraction index is η

CALCULATIONS OF THE SIZE OF THE HELIOSTAT FIELD AT KADOMA

According to Ali (1989), the main design consideration and problem in heliostat field design is shading and blocking. Ali (1989) also says that the higher the height of the tower, the smaller the shadowing length, but this will increase construction costs and instability given strong winds and storms.

The heliostats must supply 500 MW plus losses

20% is the assumed overall plant efficiency.

20%=500 MW

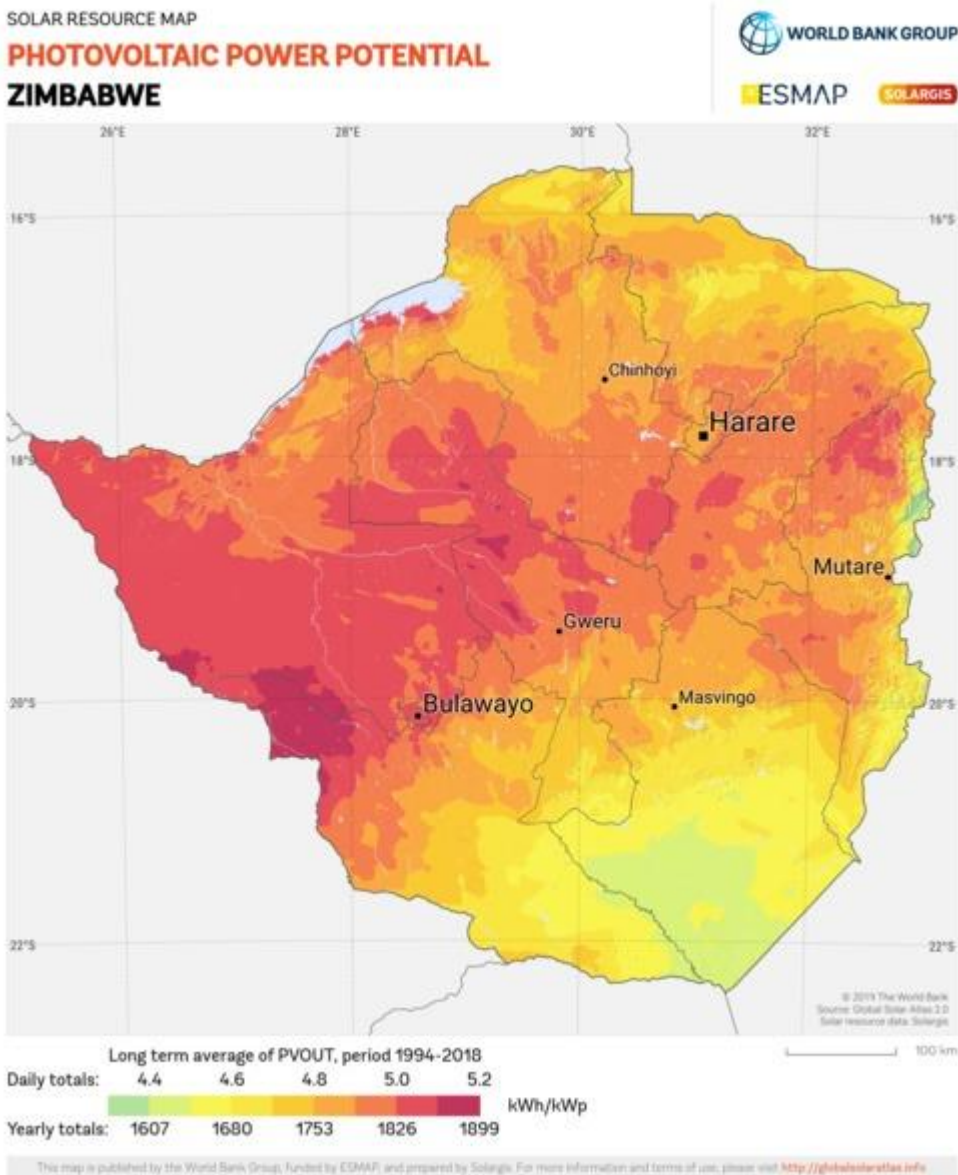
100%=?

$$\frac{100}{20} \times \frac{500}{1} = 2500MW \dots$$

There is need for capturing 2500×10^6 Watts using mirrors.

Attenuation of light results from liquid and solid particles in the air e.g. humidity as solar insolation travels from heliostat to the solar absorber on top of the tower. Scattering and absorption are the methods of attenuation by solid and liquid particles.

Solar radiation in Kadoma



According to TuTiempo.net (2025), the above is the solar radiation map for Kadoma
Figure 38

The unit of measurement for solar radiation is expressed in **W/m²** (Watts per square meter).

Average radiation= 5000 Wh/m² in 10 hrs. In 1 hour=500 W/m²

The rays that are reflected also undergoes via atmospheric attenuation before hitting on the receiver.

In order to output 500 MW that is injected into the grid, there is a quest to capture 2 500 MW by the mirrors for design purposes.

Let the solar intensity =x Watts per square meter and area of a single heliostat be =A m². Energy trapped per heliostat =Ax

Number of heliostats required $r = \frac{2\,500\,000\,000}{Ax} = \dots$

According to Cruz et al (2017),

the total Reflecting Area(A)= $\frac{E_p}{N_{opt} \cdot N_{rec} \cdot N_{conv} \cdot DNI}$

$\eta_t = \eta_{opt} \cdot \eta_{rec} \cdot \eta_{conv} = 20\%$ = power station overall efficiency

Where E_p = total electric power (500 MW)

N_{opt} = optical efficiency of the heliostat

N_{rec} = solar Receiver efficiency

N_{conv} = conversion efficiency of the power block/heat engine

DNI = Direct normal irradiance at the local area where the plant is situated

Receiver efficiency transpires at the solar absorber. The optical efficiency transpires at the mirrors and conversion efficiency happens at the heat engine or power block.

The space between heliostats is assumed to be 20% of the heliostat area in order to minimize shading and blocking.

A mechanical mechanism helps in a two dimensional rotational dynamics of the reflecting surfaces in other heliostats. The heliostats surface spins 15 ° per hour whereas another axis allows adjustments which are manual to compensate for declination changes across seasons.

According to Noone et al. (2011), The optimal efficiency of heliostats is dependent on (a) shading and blocking between consecutive multiple heliostats (b) receiver interception (c) heliostat reflectivity (d) cosine losses (e) atmospheric attenuation occurring between heliostat and solar absorber. Ali (1989) says that shading occurs when sun's rays cannot access the surface of a heliostat or mirror due to intercept by another heliostat or mirror. Blocking happens when solar flux that is reflected is blocked from reaching the solar absorber which is targeted by another mirror or heliostat.

According to Collado and Guallar (2015): -

$$\eta_{opt}(x, y, t) = \rho \cos w(x, y, t) f_{att}(x, y, t) f_{sb}(x, y, t, \text{neighbors})$$

Where

η_{opt} = instantaneous optical efficiency

ρ = effective mirror reflectivity

$\cos w$ = the cosine of the incidence angle between the sun's rays and heliostat normal

f_{att} = atmospheric attenuation

f_{int} = the intercept factor i.e. the fraction of the energy spot sent by the heliostat that hits onto the receiver surface.

f_{sb} = the blocking and shading factor that is equivalent to the heliostat area that is free of blocking and shading.

If h_{cos} = Cosine losses

T_{sb} = shading and blocking losses

T_{itc} = interception of sun's rays at the aperture

T_{aa} = atmospheric attenuation

τ_{ref} =heliostat reflectivity

$$\tau = \tau_{cos} \cdot \tau_{sb} \cdot \tau_{itc} \cdot \tau_{aa} \cdot \tau_{ref}$$

Heliostats that are far away have lower efficiency than heliostats near to the tower (Noone et.al., 2011)

According to Cruz, and Redondo et al (2017), the following Software packages or tools are for analyzing and optimizing optical performance of Heliostat solar fields:

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- HFLCAL
- DELSOL
- Tonatiuh
- NSPOC
- Hops

Kadoma

Average Wind Speed=10km/Hr

Average temperature=24 °C

Average Solar Irradiance = 18 MJ/m²/day (16 MJ/m²/day to 22 MJ/m²/day)

1 Watt=1 Joule per second

1Kw= 1 000 J/s

1MW= 1 000 000 J/s

1 MW=1 MJ/second

18MJ=18MW/m²/day. Sunshine for 10 hrs a day

10x60x60 sec=1 day

$$\text{Solar Insolation} = \frac{18\,000\,000}{10 \times 60 \times 60} = 500W/m^2/sec$$

The overall plant efficiency is taken to be 20%,

20%=500MW

100%

$$\frac{100 \times 500}{20} = 2500 \text{ MW}$$

If P = output power of the power station = 500 MW = 500 000 000 W

η = overall efficiency of the power station = 20% = 0.2

S = solar intensity level at Kadoma = 500 W/m²

A = area of one heliostat

1.2 = factor to prevent blocking and shading

Number of heliostats needed using 140m² heliostats = $2500000000 / (500 \times 140) = 35715$ heliostats

$$\text{Total Area needed} = \frac{1.2P}{S\eta} = 6000000 \text{ m}^2$$

Mirror dimensions - 140 m²

Number of mirrors required = $6000000 / 140$

With radial staggered, $\pi r^2 = 6000000 \text{ m}^2$, $r^2 = 1909090$, approximately = 2000000, $r = 1500 \text{ m}$

With a single tower the maximum radius = 1.5 km

With double towers maximum radius = 1 km

With 5 towers maximum radius = 650 m

Design for the 5 tower

Using heliostats of 140m² (i.e. 12m x 12m), assuming nothing is installed in the first 50m radius reserved for energy storage tanks and turbine, the maximum radius = 700m

The radii for the 5 tower will be spaced by 3m i.e. 15m from centre of heliostat to the centre of another heliostat to minimize blocking and shading as follows

(50, 65, 80, 95, 110, 125, 140, 155, 170, 185, 200, 215, 230, 245, 260, 275, 290, 305, 320, 335, 350, 365, 380, 395, 410, 425, 440, 455, 470, 485, 500, 515, 530, 545, 560, 575, 590, 605, 620, 635, 650, 665, 680, 695 and 710 m) from the tower in a radial staggered arrangement.

The radii will form concentric circles surrounding the tower with the first being 50m radii from the tower and the furthest being 710m from the tower.

The power station with 5 towers will be far more efficient than a power station with one tower or two towers and therefore is the more preferred configuration. The foundations of the supporting structure and the heliostats must be resilient and strong enough to endure the forces of the wind, earthquakes including storms.

Pads of those heliostat supporting structure should therefore be 2m deep into the ground. Each tower will produce at the output of the power plant of 100 MW.

Alternative working

Assuming a 20 % overall power station efficiency, we want to design a 500 MW power plant which needs $= \frac{2500\,000\,000\text{W/sec}}{500 \frac{\text{W}}{\text{m}^2}/\text{sec}} = 5\,000\,000\text{m}^2$ of mirror area is needed.

To avert blocking and shading of one heliostat by another $\frac{1}{4}$ of space must be empty = 1 250 000

Total area required for heliostats = 6 250 000m²

In the configuration of radial staggered, the heliostats could be arranged in circles, therefore

$\Pi r^2 = 6\,250\,000$. For single tower $r^2 = 1\,988\,636$, $r = 1\,400\text{m}$

For dual towers $2r^2 = 1\,988\,636$ 2 000 000 (r=1000)
 $r = 1000\text{ m}$

The inner radius is reserved for condenser, central receiver tower, control room and thermal energy storage tanks which means $r = 1\,050\text{ m}$ for single tower. $R = 1\,050\text{ m}$ for dual tower approximately 1050 m radius

Concentric circles will be formed by the heliostats. The inner circle being 50m away from the tower and the furthest at 1050m from the tower. Using heliostats of size = 140m² each (about 12mx12m). We leave the first circle with radius 50m for heat storage tanks, control room and power block, 6m for that other side of the heliostat and 3 m to minimize shading and blocking making 59m the first circle with radius 59m

The Heliostats circle radius = (59, 74, 89, 104, 119, 134, 149, 164, 179, 194, 209, 224, 239, 254,

269, 284, 299, 314, 329, 344, 359, 374, 389, 404, 419, 434, 449, 464, 479, 494, 509, 524, 539, 554, 569, 584, 599, 614, 629, 644, 659, 674, 689, 704, 719, 734, 749, 764, 779, 794, 809, 824, 839, 854, 869, 884, 899, 914, 929, 944, 959, 974, 989, 1 004, 1 019, 1 034, 1 049, 1 064)

The radial staggered field layout at above radii are proposed.

According to Luis and Francisco (2020), single tower power plants are limited in size due to atmospheric attenuation and cosine losses. It is wiser to split the solar field into modular multi-tower configurations. The above power station may as an example comprise of 5 tower and fields with common thermal energy storage and heat engine. Each field to generate 100 MW

Assuming a 20 % efficient plant

$$5 \pi r^2 = 1\,988\,636 \text{m}^2$$

$$r^2 = 126\,550$$

$$r = 356 \text{m}$$

5 As a result of cosine losses and atmospheric attenuation, solar fields with 5 towers of radius 356 m each with a height of 240m becomes more efficient than one field with 1400m radius with tower 240m high. The 5 tower configuration is not recommended for this project because of cost, whilst the single tower plant is recommended.

PV for Comparison

Research from local shops showed that 3mx2m PV polycrystalline solar panel has an output of 550 W, what would the field of area 6 000 000 m² produce. Simple proportion

$$6 \text{m}^2 = 550 \text{W}$$

$$6\,000\,000 \text{m}^2 = ?$$

$$\frac{6\,000\,000}{6} \times 550 = 550\,000\,000 \text{W} = 550 \text{MW}$$

$$\text{Number of solar panels required} = \frac{6\,000\,000}{6} = 1\,000\,000 \text{ panels}$$

Each solar panel costs US\$120

ITEM	UNIT COST(U.S. \$)	TOTAL COST(U.S. \$)
1 000 000 Solar Panels	120	120 000 000
1 000 000 Panel stands	500	500 000 000
Cost of labor	40 000 000	40 000 000
Cost of Transport	20 000 000	20 000 000
Maintenance Costs		100 000 000
Subtotal		780 000 000
5 % Admin Costs		39 000 000
<u>Total Cost for the P.V. Power Plant</u>		<u>819 000 000</u>

But the Central Receiver Tower Power plant will give us 500 MW which is slightly lower than PV Photovoltaic of comparable size. The only disadvantage of PV is that that there is no generation at night and also during cloud cover which gives the Central Receiver Tower power plant an advantage over PV. Large quantities of energy cannot economically be stored in batteries, but can economically be stored as heat and hence why the project concentrated on Central Receiver Tower Power Plants and not P.V.s. Photovoltaics cannot be coupled to heat energy storage which is a setback. The variation in P.V. output can cause grid instability because of stochastic sunlight.

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Force on Heliostat Structure

The wind's average speed = $10 \text{ km/hr} = (50/18 = 2.778) \text{ m/s}$

The wind's average force = $\frac{1}{2}mv^2$, $m = \rho V$, $F = \frac{1}{2}(\rho \times \text{volume}) V^2$, density of air = 1.293 kg/m^3

Force due to wind = $\frac{1}{2} \times 1.293 (140 \times 1) \times (50/18)^2 = 502 \text{ kgm/s}$

$F=502$ Newton second

The support structure of the heliostat must be capable of handling about 550 Newton second. It is proposed that the support structure of the heliostat must be 2 m deep so as to be capable of withstanding forces due to wind and likely earthquakes.

This means

Heliostat Sizing

The main considerations in dimensioning and sizing heliostats considering wind: -

- Heliostat posture, position and its size relative to the wind's direction of blow.
- Size of the heliostat
- Deformations whilst in operation
- Wind and storm loads
- Accuracy of tracking

The heliostat subcomponents and their functions are as below: -

Pylon and foundations for connection to the ground, mirror support structure for mirror position and shape, control for determination of offset, drives for mirror panel rotation and mirrors for reflection and interception of sunlight

According to Sattler et al (2023) heliostat field can be calibrated using a Laser and Camera system

Which can also be used to measure reflectivity by evaluating the reflections of laser light on dust on the mirror facet. Laser safety is the major challenge.

Key Assumptions Made

- (1) The average solar flux or solar intensity at Kadoma is always 500 W/m^2 . In practice solar irradiance varies daily from morning(sunrise) to noon to sunset. Solar intensity levels also vary with season. An average value was employed in the above calculations

- (2) 140 m² heliostat mirrors will be available and used.
- (3) Dual-axis solar tracking was employed rather than a single-axis and will always be functioning without fault.

Conclusions

The field of the heliostats for a 500 MW power plant is huge and multi-tower designs help reduce these fields. The main losses in a heliostat field consists of reflectivity losses, atmospheric attenuation, cosine losses and spillage. In order to generate 500 MW, the maximum circle radius for single tower=1 400m, for dual tower 700 m and for five tower=356 m. Reflectivity of mirrors and heliostats can be determined by using a laser and CCD camera. Areas for future research includes how to increase reflectivity of heliostat mirrors, improvements in tracking technology and how to minimize shading and blocking.

The project now proceeds to discuss the solar tracking mechanism

3.2 SUN TRACKING MECHANISM



Figure 39

The mechanism above will have a solar panel installed on top for solar vector identification or a heliostat mirror of size 140 m^2 . In addition, each mechanism will have an Arduino microcontroller. Each heliostat mirror mechanism and solar panel mechanism will have a HC-12 radio transceiver for facilitating communication. Our solar trackers with solar panels will be installed at South, North, West and East of the outward side of that heliostat mirror field of 35 715 heliostat mirrors. The four solar trackers are for identifying the sun vector. They communicate with each other and the North solar tracker will calculate the average sun vector and broadcast this solar vector to all heliostat mirror support mechanism's Arduino controllers to give the sun vector which is the same for all heliostats since the sun is very far away. The Arduino controller for each heliostat mechanism will average this vector of solar rays and the solar absorber vector to find that needed normal vector for each heliostat mirror and give command to each d.c. for actual or stepper motor for prototype to position each heliostat having and satisfying this normal. The L293 D chip will drive the stepper motor in the prototype. Specifically, we will employ HC-12 radio transceivers from RS232 for North solar tracker to all heliostat mirrors. The GPS coordinates for the solar absorber and each heliostat mirror will be known in advance in order to calculate the receiver vector from each of the heliostat mirrors.

HC-12 is a serial port wireless radio transceiver communication module. It is employed in industrial remote control. For communication of among solar trackers and the North solar tracker and all heliostat mirrors, we use HC-12 radio transceivers from RS232.

Features of HC-12

1. Can communicate upto 1 km in open space. Its baud rate is of the order of 5000 bps within air. Its range of working frequency is (433.4-473 MHz) and can operate upto 100 communication channels.
2. Communication with external devices via serial port and transmission of data is done serially. It works with an Arduino and modem.
3. RS-232 transceivers enhance protection of the system and increase data rates whilst reducing power consumption.

EQUIPMENT NEEDED

1. Heliostat mirror and solar panel support mechanism ((35 715 +4=**35 719 units**)
2. 35 715 Heliostat mirrors (140 m²)
3. 1 Central Tower
4. 1 Solar absorber or RECEIVER
5. 35 719 Arduino MEGA microcontrollers
6. 35 719 D.c. and NEMA 34 stepper motors
7. 35 719 Transceiver
8. 16 Light Dependent Resistors(LDRs) for the 4 solar Trackers-West, East, South and North of the heliostat mirror field

EQUIPMENT NEEDED FOR STEPPER MOTOR CONTROL for semi-spinning or SEMI ROTATING THE HELIOSTATS

1. 12 V Ronny transformers
2. 10 K Ohm 0.25W Resistors
3. 25 V 1000 micro farad Capacitors
4. TIP 2955 POWER transistors
5. TIP 121 npn Darlington pair of transistors
6. TIP 127 pnp Darlington pair of transistors
7. 4 of 6A diodes
8. 7812 of 12 V regulator
9. 7805 of 5 V regulator
10. 2 of 7 ohms 1 Watt resistors

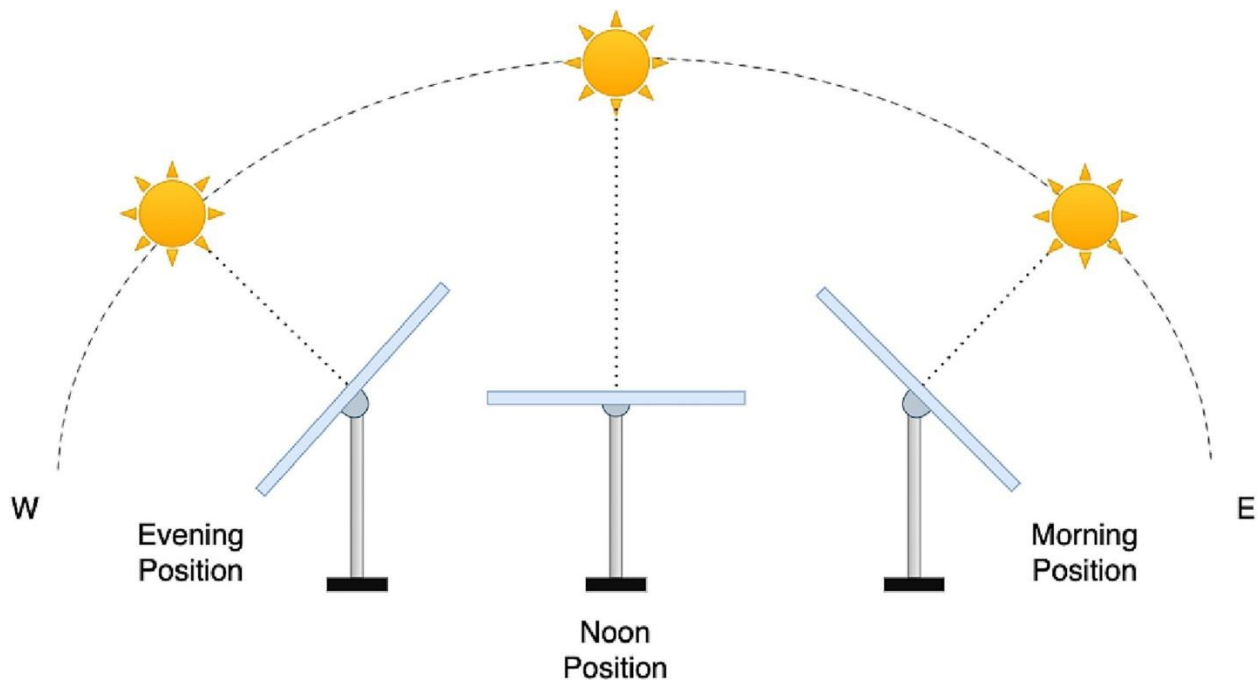


Figure 40

Comparison of dual-axis tracking and Single-axis tracking

- (1) Single-axis tracking is simpler while dual-axis tracking is complex
- (2) Single-axis tracking is cheaper while dual-axis tracking is more costly
- (3) Single-axis tracking tracks in only one-dimension East-West or North-South whereas dual-axis tracking tracks in 2 Dimensions i.e. East-West and North-South simultaneously
- (4) Dual-axis tracking is more efficient than single-axis tracking

Introduction

According to the design of heliostat solar field, 35 715 heliostat mirrors of size 140 m² will be required to be installed with a field radius of about 1.5 km. In addition, 4 solar trackers will be required for calculating the average solar vector or sun's direction from the power plant. Communication and handshaking of signals will therefore be required, this implies that telecommunication knowledge, skill and wisdom will be required in this project

A signal is any variable with some information. in our case the signal may be light, electromagnetic wave, electricity, radio wave etc.

For communication to occur there are 3 participants (1) information source and transmitter (solar tracker, receiver and heliostat tracking mechanism) (2) communication channel or communication link which may be fibre optic, copper or aluminum wire or wireless and (3) the information destination or information sink. The communication channel may add noise (unwanted signals superimposed on the intended signal) in the process of signal transmission from source to information sink. In our project there is a signal from the three sun trackers to the north solar tracker. There exists communication again from that North solar tracker to each of the 35 715 heliostat mirrors' HC-12 transceivers. There is communication from the transceiver to the Arduino controller of each heliostat mirror mechanism. There is communication from the Arduino controller to the d.c. and stepper motors. The

stepper and d.c. motors through a mechanical transmission system involving gear wheels then semi-spin or semi-rotates the heliostat mirrors so that their normal is the average of the sun vector and the receiver vector.

For this project radio or wireless communication has been selected for sophistication, modernization and in order to minimize costs and the other channels require digging trenches-filling and backfilling labor apart from the costs of the link costs like copper aluminum and fibre optic.

ADVANTAGES OF RADIO OR WIRELESS COMMUNICATION LINKS/CHANNELS

1. Mobility-communication may occur with one or both of the information source and information sink moving (within signal reach)
2. Installation is easier and faster compared with wired systems
3. Scalability –can be expanded easily to accommodate other additional information sinks and devices
4. Cost-effectiveness –less costly to set-up and install than wired options
5. Flexibility-Irrespective of the power station infrastructure, wireless systems could be installed anywhere
6. Stability and Speed-Wireless or radio system possess stability and enhanced speeds.
7. Clarity of communication-it has full duplex capabilities (i.e. two-way communication ability)
8. Independent of use of wires or physical links.
9. Can be set up easily
10. Global and better coverage e.g. with the establishment of Star-link and other satellite communication
11. Portability and transportability of information source transmitter and information sink receiver
12. Easier ‘Network planning’ compared to wired systems
13. Expandability -ability to serve a huge number of information sinks without depending on new additional equipment or hardware.

DISADVANTAGES OF WIRELESS OR RADIO COMMUNICATION LINKS

1. Security problems
2. Not as reliable as wired networks
3. Prone to interference problems
4. Probability of jamming is higher
5. Less transmission speed
6. Limited bandwidth
7. Hacking vulnerability
8. Installation costs high, setting up costs of wireless network is costly
9. Most people not yet past the learning curve on wireless system design and installation

ADVANTAGES OF FIBRE OPTIC COMMUNICATION

1. Speed of Communication-Ability to attain higher speeds going upto 10 gigabits per second.
2. Distance-fibre optic has ability to transmit information or data across tens of kilometers in comparison to cables of copper which can attain a maximum or pinnacle distance of 100m
3. Security-Communication involving fibre optic cables is hugely secure
4. Bandwidth-compared to copper cables, fibre optic cables possess a bigger bandwidth.
5. Electromagnetic Interference- fibre optic communication is highly resistant to interference due to electromagnetic waves
6. Reliability-Better reliability of fibre optic cables compared to alternative methods
7. Maintenance-Possess lower costs of maintenance
8. Scalability-hugely scalable
9. Compatibility-has compatibility with existing technologies e.g. VoIP and WIFI systems

10. Flexibility- Fibre optic cables are thinner and lighter in comparison to copper cables thereby becoming less prone to damage and having more flexibility
11. Raw Materials –silicon that is sand which is sand which is the raw material for quartz optical fibre is nearly inexhaustible within nature.

DISADVANTAGES OF FIBRE OPTIC CABLE COMMUNICATION

1. Cost-compared to copper cables, fibre optic cables are comparatively costlier to install. Fibre optic cables need specialized knowledge and specialized test equipment.
2. Fragility-since fibre optic cables are constructed from glass, they are therefore more fragile in comparison to cables of copper. Breakage of fibre optic cable strands can happen if cut accidentally or bent too much during installation and construction.
3. Splicing- splicing of fibre optic cables involves a process which is highly delicate which could disrupt communication network if it is not done carefully and properly.
4. Light signal Attenuation-light signal's energy is diminished during the process of transmission across longer distances.
5. Dispersion-signals flowing in optic fibres are spread out across time.
6. Fibre Fuse-too much light could encounter an imperfection in fibre optic at high power.
7. Propagation of light Unidirectional-propagation of light in fibre optic cables can only happen in one direction
8. Safety-the sharpness and thinness of fibre optic strands makes them almost impossible to be seen, and can injure the skin by piercing or get into eyes or contaminate drink or food.
9. Infrastructure Disruption-existing infrastructure can be disrupted by installation and therefore planning and coordination need to be done carefully.

ADVANTAGES OF COPPER WIRE COMMUNICATION

1. Conductivity-in terms of conductivity, copper metal is only second to silver and therefore can efficiently transport electric energy more compared with other materials.

2. Corrosion-Resistance- Copper can resist corrosion which diminishes chances of failure and deterioration. Copper cables could avail reliable and strong connection for a long time
3. Malleability-ability of copper to bend to conform to any shape whilst not breaking and therefore has ability to be twisted around corners and made into shapes which can fit in availed space.
4. Ease of Installation-copper is simple to install without requiring specialized tools, joint compounds, washers or pigtails.
5. High Tensile Strength-Copper possesses high tensile strength and is strong thereby making it suitable for signal sending over long distances
6. Cost Effectiveness-less expensive compared to fibre optic.
7. Low Maintenance-copper connections corrode or loosen less likely over time and need less maintenance.
8. Eliminates crosstalk-there is mitigation of crosstalk in pairs of twisted copper cables and efficiently transmit data
9. Compatibility with most existing infrastructure-copper wire is frequently compatible to existing infrastructure making it ideal for modernizing outdated networks.
- 10.Heat Resistance
- 11.Ductility

DISADVANTAGES OF COPPER WIRE COMMUNICATION NETWORKS

1. Signal interference-copper wire communication links can easily pick up noise generated in nearby networks and devices e.g. electrical systems, computers and phones. Signal distortion and signal weakening results from the above particularly across longer distances.

2. Limited Distances-Copper wires are not employed in multiple applications e.g. multiple floor buildings. Cat8 copper cable permits communication over a restricted distance of 30m.
3. Bulkiness-copper wires and cables are bulkier than fibre optic cables, creating difficulties in moving them from one area to another.
4. Fire and Shock Hazards-copper wires employ electricity to transmit information point to point and can therefore pose risks of fire and shock hazards.
5. Electromagnetic interference-electromagnetic current can be produced by copper cables which results in electromagnetic interference or noise over the network.
6. Handling-one can be injured by incorrectly handling copper cables and wires.

After above analysis wireless communication has been recommended for the Central Receiver Tower Power Plant i.e. between solar trackers, between North solar tracker and all heliostats mirrors and between heliostat mirrors and receiver.

The project now proceeds to the design of the central Tower.

3.3 DESIGN OF A 240m HIGH CENTRAL TOWER FOR A 500 MW SOLAR POWER TOWER PLANT TO SUPPORT THE RECEIVER

INTRODUCTION

The aim of this part of the project is to: -

- Analyze forces that may act upon the tower and a discussion of vital considerations to be taken into account in designing the tower.
- Design the foundation pad for the 240m high tower, the tube-work to carry the Thermal energy transfer fluid up and down that tower, including sizing the electric motor to pump the HTF up and down the tower including ladder up and down the tower.

This section involves the discussion of the technical design of the foundation pad for a 240m high Central Receiver tower for a 500 MW CRT power plant, design of the support structure i.e the tower stem and the design of the receiver or solar absorber support. The design is for (1) a complete single concrete reinforced tower entity and (2) a complete steel tower. The section posits that the tower is designed to ensure power plant efficiency as well as reduce construction costs. The efficiency of solar trapping by the solar absorber is a function of tower height and meteorological conditions, solar field efficiency including cosine efficiency, shading and shadowing efficiency, atmospheric attenuation efficiency, receiver control strategy and wind speed.

An analysis of the static and dynamic forces on the structure are analyzed in order to inform the design e.g. forces due to weight of the tower assemblage, the upward, equal and opposite reaction force of the ground, wind forces and equal and opposite ground/soil forces. The section posits that the balancing of these forces is essential for stability, enhanced life expectancy and durability of the central tower. Contribution of resonance to tower instability is also considered.

The section also analyzes the pipework for upward (to receiver) and downward (to heat storage tanks) transportation of the Heat Transfer Fluid and associated electric motors.

MAIN NARRATIVE

The Central tower is a tall structure which supports the solar absorber and puts or positions it in an ideal position where it can be accessible to almost all the sunlight reflected from all the mirrors or heliostats in the field. It can be purely civil, mechanical or mecha-civil structure. In tower design, precautions should be taken to guarantee that minimum of its surface area is exposed to wind forces so that minimum wind impinge on its structure.

It can be a steel or steel-concrete structure although the steel reinforced concrete structure is preferred.

It is required to ascertain the wind's direction and speeds at the proposed site of the power station to facilitate calculations and computation of the forces of the wind that the tower will be subjected to.

Because it is frequently central to the heliostat field, it is called the Central tower.

According to Kayvani (2014), the Council on Tall Buildings the threshold for the following is defined for buildings as follows: -

Upto 200m-tall structure

upto 300m –super tall structure

upto 600m-mega tall structure

Kayvani (2014), says the following forces need to be considered in the design: -

- Gravity effects which are acentric
- Likely earthquakes
- Wind

- Lateral earth pressures which are unbalanced that could be imposed onto the foundation in any given direction.

Alavi et al. (2017) says that the criteria of strength are less crucial than dynamic responses in the design of slender and tall structures. Resonance is a threatening phenomenon. To avoid this likely disaster, the fundamental Eigen frequency i.e. the eigen-frequency of higher order should be maximized.

The tower for a Power Tower power plant is constructed in such a way as to avail an appropriate, ideal and proper height which is accessible freely by all rays of the sun from the surrounding mirrors or heliostats. The solar absorber that is supported by the tower's top must possess an unobstructed line of sight with all heliostats and mirrors in the power station. The receiver which is also known as thermal energy collecting element or solar absorber which is at the tower's top is the heat pivot and the focal point for heat production for the power station.

Modular construction can be considered for the Central towers. It consists of prefabricated units that are usually fitted at manufacture and installed at site as load-bearing units. According to Lawson (2010), the advantages of such are as follows: -

1. It is economic to manufacture repeated units.
2. Installation on site is done at high speed'
3. Improved accuracy and quality during manufacture;

The target sun altitude angle of the solar absorber for each heliostat (α_r) which is described by the height of the tower (H) and the heliostat distance from the ground i.e. its height(h) and the Heliostat distance from the tower base(R). The targeted receiver location on the top of the tower is also defined as the azimuth angle (γ_r) which is defined as the relationship with respect to the North direction of the Heliostat and tower.

The Central Tower is where the name of the power plant type is derived. Application of the studies in Soil Mechanics and compaction ratio of the soil taken together with the height of the tower may be necessary to determine the depth of the foundation pad into the soil. Soil tests need to be done to ascertain the needed foundation pad depth.

The following tests need to be done:-

Electrical tests

- Soil resistivity tests

Structural/Civil tests

- Sieve analysis –particle size soil tests
- Plasticity index tests-to determine forces within particles
- Sheer-box test- to determine after what amount of pressure does the soil sheer-pressure on soil
- California Bearing ratio tests-to ascertain soil strength (soft or hard soil)

The structural load emanating from the weight of the tower, ground water table, nature of soil and wind speed and direction determines how deep the tower pad will be. Hard soil and soft soil dynamics as one goes deeper into the ground also determines how deep the tower foundation pad will be. There might be a requirement for a ring beam depending on the type of soil in the foundation pad.

The nearer the heliostat is to the Central Tower, the bigger the solar field efficiency is. As the tower's height increases, so does the solar field efficiency., but the field efficiency tends to level off with increase in tower height. Power production capacity becomes larger with increase in tower height but flattens or levels off gradually with the increase in the tower height. Construction costs also increase with increase in height (construction steelwork, piping etc)

All theories of soil mechanics, theory of structures, compaction ratio must be satisfied by the foundations of the Central Tower. The tower must be mechanically resilient and mechanically sound so as to withstand all forces that may impinge on it from lightning strikes, earthquakes, thunderstorms, rain and wind. Wider and deeper foundations for the tower are needed in areas where earthquakes have previously been recorded or are most likely to occur.

A 200 m high Central tower might need a 10m x 10m deep foundation pad. Steel alloy members might allow easy through passage of wind and may not block the wind from passing. As a result, there is reduction of wind forces unlike in concrete or block towers which are continuous,

Lightning protection systems may be required in steel tower. An electric lift or ladders inside the tower may be needed to help in climbing the tower when necessary. Tubing and piping for allowing motion of the Thermal Energy Transfer Fluid down including up that tower are also designed in this project.

The solar absorber on Central Tower's top must be sufficiently secured onto the tower to forbid falling when exposed to wind forces and thunderstorm forces.

The tubing and piping from the tower's top to ground and the Heat Storage tanks require to be insulated thermally.

The tower members should be built using carbon steel. They shall be of enough mechanical strength to adequately carry the receiver and the thermal Energy Storage Fluid together with wind forces.

Deformed steel bars of the NEXUS or ECO are employed to make and design reinforced concrete that constitute the tower pad foundation. Cement, deformed steel bars, stone and sand makes the tower pad.

FORCE FIELD ANALYSIS

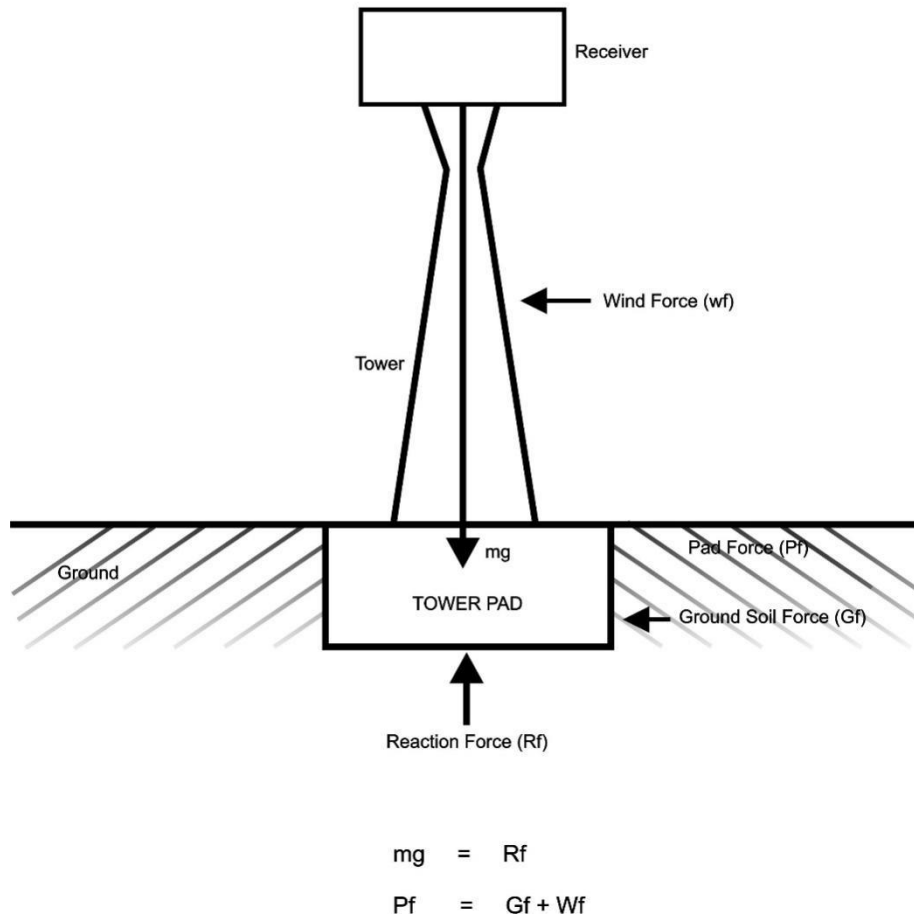


Figure 41

The density of steel= 7.85 g/cm³

Assuming the 200m tower is constructed with 0.3m wide and 0.8 m long and 205m high

Volume of steel used for the 4 corners=200x0.3x0,8=48 m³

Supporting steel=200x0.4x0.2x2=32

steel members for Receiver =6x4x4=96m³

$$\text{Total steel volume}=48+32+96=176\text{m}^3$$

$$\text{Density}= 7850\text{kg/m}^3$$

$$\text{Weight of steel}=176\times 7850=1\,381\,600\text{ kg}$$

$$\begin{aligned}\text{Force into the ground due to weight}&=mg=1\,381\,600\times 9.81\text{Newtons} \\ &=13\,553\,496\text{N}\end{aligned}$$

$$Mg=R_f$$

$$P_f=G_f+W_f$$

For static and dynamic balance

$$\text{Area exposed to the wind}=0.3\times 0.4\times 200\times 2+ 0.3\times 0.5\times 200\times 2=48+60=108\text{m}^2$$

$$\text{Wind speed at Kadoma}= 8\text{km/h}$$

$$8000\text{m}/60\times 60=2.3\text{m/s}$$

$$\text{Volume of air striking steel bars}=108\times 2.3\text{m}^3=285\text{m}^3$$

$$\text{Density of air}=1.3\text{ kg/m}^3$$

$$\text{Forces due to airwind (Wf)}=1.3\times 285=367\text{ N}$$

PAD Design & Construction

There is need for a table or wooden bench dug into the ground near the tower base for bending and cutting NEXUS or ECO steel rods in order to make stirrups required to shape the steel cubes or steel cuboids for the pad and columns. NEXUS or ECO steel rods which are square in shape are known as stirrups which are spaced 20 cm apart on the 4 or more rods of steel. Steel which is mild possess a sheer strength of 400 MPa. Pouring of concrete will be done so as to ensure that concrete will be outside as well as inside the NEXUS or ECO cuboids. The process of shattering shapes concrete beams. In order to guarantee complete verticalness or horizontalness of structures, there is a requirement to employ builders' line and spirit level for obtaining profiles.

There is need for digging a 10X10X10 m hole. Meshed NEXUS or ECO deformed steel rods are placed inside the hole forming cubes or cuboids where steel rods of the tower which are vertical will be fastened to. These stirrups require to be bound onto the vertical steel rods by soft wire.

TUBING DOWN AND UP THE TOWER FOR HEAT ENERGY STORAGE TANKS

Refractory brick material will be contained in the innermost of the tubes, with the tubes of silica being just after and ultimately tubes of steel on the outside. Potassium nitrate is prevented from chemically reacting with steel by the refractory brick material whereas tubes of silica avails thermal insulation to avert heat losses to the atmosphere.

500 MW must be able to be delivered by the pipes.

Let the mass of potassium nitrate flowing per second be =m g per sec

specific heat capacity of potassium nitrate= $1.118\text{J/g }^{\circ}\text{C}$

temperature difference= $600-200=400^{\circ}\text{C}$

$mc\Theta$ =Power Station output

where m=flow mass per second

c=specific heat capacity of potassium nitrate

Θ =temperature rise=545 °C (565-20)

$mc\Theta$ =500 000 000 W

$m \times 1.118 \times 545$ =500 000 000

m=820 600g per sec of potassium nitrate has to be pumped up per second

$\pi r^2 h \times \text{density}$ =820 600g/sec (pump rating=mgh)

If we assume a 15 radius pipe from receiver to thermal energy storage tank

$(22/7) \times (15)^2 \times 2.11h$ =820600

h=549.9 cm approximately=550cm

Density of potassium nitrate gas=2.11cm³

Assuming volumetric expansion from liquid to gas of potassium nitrate is the same as that of water 1 700.

mgh =9.81x (820 600/1 700) x 5.5

mgh =184 924 646/1 700 J(W)

Pump size=26 044W approximately 26 KW pump

Silica glass has to thermally insulate the heat storage tanks including the pipes from the solar absorber at the tower's top to the thermal energy storage tanks.

Key Assumptions Made

- (1) Wind speed is always 4 m/s at 2 m height. In practice wind speed at 2 m height varies with season with the month of August having the fastest and largest amount of wind.
- (2) Atmospheric sunlight heat energy attenuation is constant throughout the day. In practice solar flux attenuation varies from morning to noon to evening with a cosine shape.
- (3) Soil strength supporting the tower height will always have the same strength. In practice soil strength varies with the amount of moisture it has –varying from dry seasons to rainy seasons.

Conclusion

Consideration has to be taken of the speeds of the wind at the proposed site, weight of the tower, types of soils and likely earthquakes in the design of a central tower. Resonance effects have also to be taken into account

The project now proceeds to discuss Solar tracking technologies.

3.4 Advances in Solar Tracking Technologies for Photovoltaics (PV) and Central Receiver Tower Power Plants (CRTPPs)

Keywords

Solar Tracking(ST)

Concentrated Solar Power(CSP)

Central Receiver Tower Power Plant(CRTPP)

Singular or 1 Dimensional Tracking(S1DT)

Dual Tracking(DT)

Solar Flux(SF)

INTRODUCTION

Solar tracking technologies for Central Receiver Tower Power Plants (also called Solar Tower power plants or Power Tower Power Plants) and Photovoltaics(PV) Power Plants will be reviewed in this section. The aims of this section encompass (1) determining conditions which must be satisfied by the mirrors or heliostats in Solar Tower Power Plants (2) the relationship between the heliostat mirror movements and the sun's motion in the sky (3) determine different technologies for determining the solar vector (4) schemes for sun tracking and eventually determine methodologies and tracking schemes for both Solar Tower power plants and PV power plants.

This section says that there exist two methodologies for sun position tracking mechanically namely (a) dual axis tracking and (b) single axis tracking. This section posits that whilst sun tracking in Photovoltaics (PV) power plants need the solar panels to face the sun always during a clear day, in solar Tower Power Plants, the solar insolation impinging on the heliostats should always be reflected onto a fixed and stationary receiver during the whole day as the sun moves from east to west. In Power Tower Power Plants, the angle of incidence on the mirror and heliostats

should always be equal to the angle of reflection. The normal to the mirror must always equally bisect the sun-heliostat-receiver angle path of the sun's rays in the Solar Tower Power Plant. In Central Receiver Tower Power Plants, if the sun moves $2\Theta^\circ$, the heliostat mirror moves Θ° in the same direction. The tracking schemes in Photovoltaics could be employed to determine the sun's direction also called solar vector in Power Tower Power Plants and then the bisector of the sun-heliostat-solar absorber computed by computers such that the mirror is positioned at right angles to the normal. Normal to the mirror $= \frac{1}{2}$ (receiver vector angle + sun vector angle) and this is contribution to world body of knowledge since no literature perused so far has mentioned this equation.

There are 3 technologies for tracking the sun namely (1) one dependent on the passage of time (2) one based on camera images and (3) one based on solar sensors such light dependent resistors, photosensitive cells or PV cells or photodiodes.

This section posits that dual sun tracking elevation and azimuthally offers efficiency which is maximum despite the fact that maintenance and operational costs are larger than single axis or stationary(non-tracking) tracking technologies. Recent literature says that modern heliostats for Solar Power Tower Power Plants are manipulated by computers fed with details of month, longitude and latitude, day and time that calculates the bisector of the sun-heliostat-receiver angle for positioning the heliostats normal and therefore the heliostats.

The research is important as it will enable collation of numerous world's point of views in sun position tracking for Photovoltaics (PV) power stations as well as tracking in Solar Tower Power Plants for benefitting the engineering society.

3 PRELIMINARY INFORMATION FOR SOLAR TRACKING

Because of climate change considerations and the requirement of lowering the emission of gases that belong to the greenhouse gas family into the earth's atmosphere, global power utilities are moving away from electric power production using fuels that belong to the fossil group for example natural gas, coal and oil.

Concentrated Solar Power (CSP) has several advantages which include the ability to be coupled together with heat storage systems so as to address that intermittency of the solar resource and other variabilities such as daily and seasonal variabilities. A Power Tower CSP power plant requires sun tracking for several mirrors (heliostats) in order to reflect the solar flux onto a fixed solar absorber on top of a very tall tower. Solar tracking increases power plant generation efficiency.

Green electric energy production is becoming fashionable and a modernity trend amongst electric energy production options, methods and schemes. The problem is that the sun moves from East to West daily causing inefficiency in solar trapping when using stationary solar collectors. Additionally, the sun moves North- South-North seasonally. The demand for green solar generation has therefore increased demand for solar tracking technologies in order to increase efficiency and maximize generation.

The research questions are: -

- (a) What are the main methods that can be used for tracking the sun?
- (b) Can the techniques be employed in combination?

Research objectives are: -

- (a) To identify tracking methods covered in literature
- (b) Contributing to the world body of knowledge
- (c) Recommending areas for future research

The United Nations COP 26 conference recommended the decommissioning or scaling down of fossil fuel (e.g. coal) generation. Concentrated Solar Power(CSP) is

a practical alternative to coal generation of which Central Receiver Tower power (CRTP) generation is one.

As mentioned previously, Power Tower Power stations need heliostat mirrors which track the sun's trajectory within the sky in such a fashion that the sun's reflected rays will at all the time be directed onto a stationary receiver throughout the 10 Hour average day period installed on top of a very tall tower e.g. 240m high, but optimally 120m high. The sun's path in the sky (i.e. sun vector) can be tracked tilt-wise or elevation –wise (East-West) and simultaneously azimuthally (i.e. North-South).

According to Stamatescu et al. (2014), the variation in azimuth angle is greater in relation to time of day and the elevation variation relates to time or season of year.

Dual sun tracking is more complicated and more expensive, but more efficient when compared with single-axis tracking.

Alici and Turmay (2021) posits that the operation and maintenance costs for dual axis tracking is more compared to that for a single axis tracking system. Hafez et al. (2018) says that single axis tracking can only track daily sun movements but not annual movements and mainly used in parabolic trough.

Employing maximum-power-point-tracking facilitates extraction of maximum solar energy by the heliostat mirrors and enhances efficiency of the power plant (Turmay and Alici, 2021). Two motors are needed for dual-axis sun position tracking so as to follow the sun's directional trajectory in the sky from a point on the surface of the earth specifically at the power station location in the azimuth and tilt angle (Yilmaz et.al., 2014)

Mpadi et al. (2019) posits that dual axis solar trackers are also called azimuthal-altitude trackers.

According to Tharamuttam and Keong Ng (2017), the azimuth angle is the angle in the horizontal plane measured from the true North to the horizontal projection of the sun's rays as specified in Equation 1.0. below.

If ϕ =the location of the latitude

δ =sun declination angle

θ =the hour angle

Tharamuttam and Keong Ng (2017) posits that equation 1.0 and Equation 2.0 holds

$$\text{Azimuth angle} = \tan^{-1} \left[\frac{\sin \theta}{\cos \theta \sin \phi - \tan \delta \cos \phi} \right] \quad \text{Equation 1.0}$$

Tharamuttan and Ng (2017), further posits that the angle of elevation is the sun's angular height in the sky measured and quantified from the object's horizon.

$$\text{Angle of Elevation} = \sin^{-1}[(\sin \delta \sin \phi) - (\cos \delta \cos \phi \cos \theta)] \quad \text{Equation 2.0}$$

Methodology

According to Conrado (2018), active tracking uses solar sensors and chronological uses time of day, latitude, day of year and the sun's trajectory.

The method that relies on the passage of time uses Global Positioning Systems (GPS) solar absorber together with a magnetic compass to get the required data.

According to Wu et al. (2022), the satellite compass includes GPS, real-time-clock(RTC) combined with inclinometer.

It also relies on right and accurate initial positioning. Active tracking is a closed loop and the method which relies on the passage of time is open loop.

Modern systems employ hybrid techniques that combine both astronomical equations and sensors for more precise and robust sun tracking.

Conrado (2018) posits that parameters that affect the performance of solar insolation sensors include contamination, climatic conditions, solar radiation and temperature.

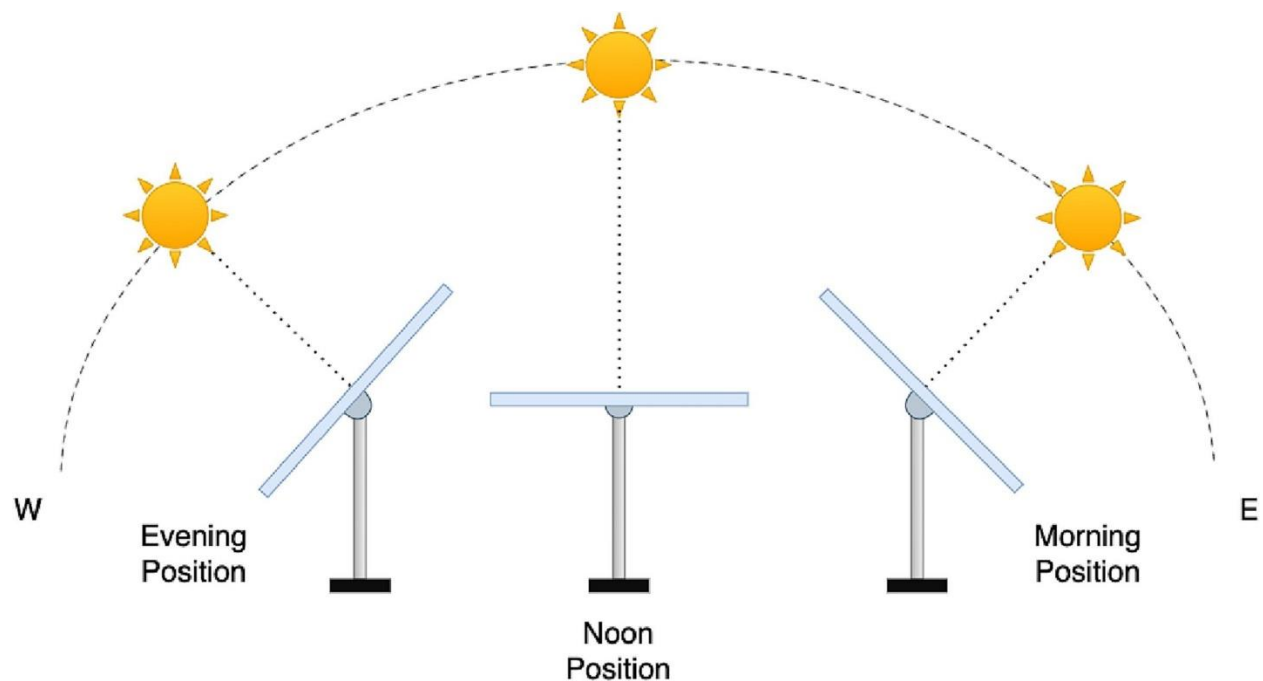


Figure 42

Mpadi et al. (2019) classifies single axis solar trackers according to how they rotate with reference to the ground surface into the categories below: - -

1. Horizontal single axis Tracker(HSAT)
2. Vertical single axis tracker(VSAT)
3. Tilted single axis tracker(TSAT) and
4. Polar single axis tracker(PSAT)

The vertical single axis solar tracker rotates in such a way as to track the east-west sun's direction. Phiri et al. (2023), posits that a solar tracker is supposed to compensate for variations in sun's azimuth, altitude and latitude. Phiri et al. (2023)

highlights that solar trackers avail an amplified solar energy yield ranging from 22% to 56 % compared to fixed technologies.

They further highlight that artificial intelligence schemes hugely affect enhanced heat capture performance of devices that track the sun.

Phiri et al. (2023) are satisfied that a typical solar tracker consists of (1) a sensing mechanism (2) tracking device (3) a tracking algorithm (4) driving mechanism (5) positioning system and (6) a control element.

Phiri et al. (2023) further posits that a tracking algorithm determines the most optimal angles using either light-dependent-resistors, astronomical tracking algorithms or image processing algorithms.

Phiri et al. (2023) further says that astronomical tracking algorithms are foundationed on the principle that the sun moves fixedly using day of the month, time of day and geometrical coordinates of the sun.

Such variables are used to ascertain and calculate the angular trajectories and movements of the solar panel so as to keep its surface perpendicular to the direction from which the sun's rays are coming from in Photovoltaics.

According to Phiri et al. (2023), image processing algorithms depend on cameras to track the trajectory of the sun in the sky.

Algorithms process such signals and the solar vector's precise position or direction ascertained and then an actuator that might be a hydraulic actuator or electrical motor is triggered to set the heliostat or panel in motion accordingly.

Phiri et al. (2023) alludes that the Light dependent resistor-based algorithm uses sensors to follow the trajectory of solar movements.

A dual-axis tracker is installed with four Light Dependent Resistor (LDR) sensors at every corner of the solar panel. Each pair's reading is compared and utilized in identifying the panel's position relative to the sun.

According to Hafez et al. (2018) tracking devices are categorized into 5 classes depending on their tracking technologies. Five categories of solar trackers are (a)

chronological trackers (b) manual trackers (c) semi-passive trackers (d) passive trackers and (e) active trackers. Hafez et al. (2018) says that a passive solar tracking gadget utilizes the heat expansion in substances or the pressure imbalance existing between 2 different points at both ends of the tracking mechanism. These materials are frequently fluids i.e. gases or liquids.

Rizk and Chaiko (2008), defines solar tracking as the activity or process of sensing and following the position and or direction of the sun.

According to Awasthi et al. (2020), solar tracking is a by-product of the quest to maximally harvest solar energy Solar tracking improves the efficiency of solar flux capture and contributes to enhanced overall solar thermal plant efficiency. According to Al-Rousan et al. (2020), tracking maximize energy output from CRT power plants.

Al-Rousan et.al. (2020) says that a sun tracker is a gadget that could track the direction of the sun in the sky from a given point on the surface of the earth and keep the solar flux absorption at optimal maxima and could maximize output power.

Alici and Turmay (2021) highlights that single axis tracking receive 30 % more solar energy compared to static technologies in P.V. power plants. The authors above also emphasize that enhancing the operational performance of sun trackers is currently a hot research area and also going into the future.

Since dual-axis sun tracking is crucial in enhancing the overall power plant performance and efficiency in Power Tower Power Plants, research must be focusing in that area (Abdollahpour, 2018). Few literature stuff covers sun tracking for Solar Power Tower Power Plants and as a result it is worthwhile to venture into that research segment in the power plant design. Different heliostat mirrors will be sited at different sites with respect to the position of the Central Tower and they must all be focusing the sun's flux onto the fixed solar absorber throughout the day.

According to Speetzen and Richter (2021), the sun's rays focused onto the solar absorber has to be uniformly distributed on the receiver so as to prevent localized hot spots which may result in damage to the receiver.

Methods

The solar tracking intelligence require to be modernized and developed. The solar flux reaching the heliostat mirrors on the earth's surface possess 2 components viz (a) diffuse or scattered flux and (b) direct flux. Direct insolation possesses 90 % of the energy of the sun whereas the diffuse or scattered flux possess approximately 10 % of the sun's energy.

So as to maximize sun's flux that is focused onto the solar absorber by the heliostat mirrors, 'direct flux' solar trackers are used. As said earlier, in Tower Power Plants the heliostat mirrors must track the solar vector in such a fashion that the reflected flux from the mirrors should always be focused onto the fixed and stationary solar absorber installed on top of the Central Tower throughout the day as the sun travels in its daily path in the sky. The reflected angle on the mirror to the solar absorber and the angle of incidence of the sun on the heliostat mirror must continuously be the same.

Al-Rousan et al. (2020) classifies solar trackers into two categories namely manual and automatic, Awasthl et al. (2020) posits that sun trackers could be classified pivoted on drivers employed, system of control applied, tracking technology or on the basis of the number of degrees of freedom availed.

Awasthl et al. (2020) posits that dual sun trackers need 2 degrees of freedom mechanism in order to orient the mirrors accordingly.

The difference between single-axis tracking and dual-axis tracking in terms of efficiency was observed to be three to five percent for PV power plants (Muhammed et.al., 2020). The efficiency of single axis trackers is twelve to twenty percent greater than the fixed axis heliostat mirror systems.

The expenses of the heliostat to the total installation cost is about 40% to 50%(Shyam & Ghosal (2017))

Also according to Shyam and Ghosal (2017), ‘the latitude, longitude, altitude of the heliostat, time and date are fed into the computer.

One uses the astronomical theory to calculate and compute the sun’s direction i.e. the solar vector from the heliostat mirrors. Modern heliostats are regulated and controlled by computers which compute the bisector of the sun-heliostat-solar absorber angle and then adjust the heliostat so that it becomes perpendicular to this bisector. All mirrors in the heliostat mirror field are normally controlled by one computer.

According to Chen (2020), the other method involves pointing one axis of the tracker towards celestial north pole which is parallel to the earth’s rotational axis.

The alternative axis is configured to be perpendicular to the declination also called the polar axis. During operations, mirrors rotate around the polar axis ensuring that the speed of rotation is same as the earth’s rotation angles, except that the direction of rotation is opposite (Chen, 2020).

One can employ an object’s shadow at the heliostat in order to track the relationship between the object’s length and the shadow’s length and the azimuth angle is employed for elevation tracking and the shadow’s position from North could be exploited for quantifying the azimuth angle (Awasth et.al.,2021)

Redemacher et al. (2019) posits that in other solar trackers the azimuth angle is tracked by a structure on wheels on a ground track.

For photovoltaic power plants solar sensors such as photodiodes, pyrheliometer, photosensitive cells or small solar panels or light sensitive resistors will be used for detecting direction or trajectory of maximum solar insolation i.e. a beacon showing the direction of the sun vector. Arturo and Alejandro (2010) proposes use of webcams as solar sensors as this method is not influenced by conditions of weather such like temperature including humidity that affect light dependent resistors and photodiodes sensors. The 4-quadrant small solar panels or light dependent resistors underneath the main solar panel on opposite sides will be wired to the controlling

motor in opposite polarity. This method is proposed by the authors of this paper to identify the sun's vectorial trajectory. The solar location at any given time from that arrangement on one position is broadcasted by a transmitter to the computer with coordinates of the solar absorber and all heliostats where the bisector of the sun-heliostat-absorber is calculated by the computer for each heliostat or controller for each heliostat for positioning the heliostat by the controlling electric motors or hydraulic actuators. In this way solar tracking for Central Receiver Power Plants is an improvement of the solar tracking in photovoltaic power plants.

It is to be noted that the Solar Photovoltaic problem where solar panels are always normal to the sun is a bit different and simpler than for the Central Receiver Tower (CRT) trackers where the mirrors do not necessarily have to be normal to the sun but must meet constraints that firstly the reflected rays from the heliostat must always be directed to the stationary receiver and the reflected and incident angle must always be equal. In other words, the heliostat mirror must always have its normal bisector of the sun-heliostat-receiver angle.

The maximum insolation level sensed by a light dependent resistor, pyrheliometer, photodiode or small solar panels is the signal that tells the heliostat controller the direction of the sun from which the heliostat is rotated to guarantee that the reflected insolation would always be focusing onto the solar absorber. The control of the solar trackers will be analyzed and the mathematics of control of the heliostat derived from first principles.

We have one known constant vector from the heliostat to the receiver also called a solar absorber vector and two variable vectors in the form of the normal to the mirror vector and the solar vector from the heliostat.

According to Kalogirou (2014: p125), the sun's motion in terms of day trajectory could be easily tracked by any of the 2 techniques. The first method is the altazimuth option that needs that the device that tracks should rotate or spin in both azimuth and altitude. If performed correctly, this technique facilitates accurate and exact sun tracking. This method is also called dual axis tracking. The central receiver tower CSP uses this method. The second method is the single axis tracking in which the heliostat tracks the sun in the singular direction either from north to south or east to west. The parabolic trough collectors(PTC) usually employ this technology.

According to Kalogirou (2014), the tracking mechanisms must rotate or spin the heliostat out of focus for hazardous environment and conditions of work protection for example failure of the heat fluid flow mechanism, overheating and wind gusts. Here the knowledge of condition monitoring and protection systems becomes important.

Wind, gravity and the weight of the heliostat structure are the three main forces that acts on the foundation of the heliostat support structure. In the design of the heliostat field certain information need to be collected from the Meteorological offices such as wind speed at the heliostat position, humidity, solar intensity, temperature, and number of clear skies per year. Extreme turbulent, fluctuative wind forces may excite resonance and result in support structure fatigue failure. We have to come up with appropriate heliostat shape and orientation after considering all the above factors.

According to Kalogirou (1996), tracking mechanisms can be subdivided into 2 wide categories namely electrical-electronic and secondly Mechanical schemes.

The systems that are electronic usually have enhanced tracking precision and reliability.

These could be further sub-classified into firstly the mechanisms that employ motors that are controlled electronically via sensors, that detect the quantity of the sunlight illumination (Kalogirou (1996)) and secondly mechanisms employing motors that are controlled by computers, with feedback control offered from sensors that measure amount of sunlight on the solar absorber the solar (Briggd, 1980; Boultinghouse, 1982)).

Kalogirou (1996) developed a tracking mechanism that utilizes 3 light-dependent resistors(LDRs) that detect the focus, day-night and sun-cloud conditions and instructs a D.C. motor via a system of control to focus the heliostat to follow the approximate the sun's trajectory when there exist cloudy conditions and return the heliostat to the East during night period.

According to Kalogirou (1996), single axis tracking(azimuth) produces 25% more energy than fixed heliostats.

According to Kalogirou (1996) there are two types of trackers for P.V., firstly the ‘solar time tracker’ which acts like a watch which gets its commands from movement of time. It has a 180° rotation with limit switches on either ends east and west (for detecting sunrise and sunset). The second is a solar heat tracker which gets its commands from solar insolation/heat or rays. This type of solar tracker uses light dependent resistors (LDR), photodiodes, pyrheliometer or 4 photosensitive cells (or smaller solar panels) at the back of panels as light sensors for detecting the sun’s vector (magnitude and direction of solar insolation). From the solar vector, the angles which are dual of the heliostat to guarantee that the solar flux is always being focused onto the solar absorber are calculated by a software program and a control signal sent to the controlling electric motors or hydraulic or pneumatic actuators.

There exists single axis and full dual/double axis sun-tracking for heliostats (a) east-west (x-plane) tracking elevation, and north-south (azimuth) (x and y plane) tracking! The single axis tracking requires only one stepper motor. The double axis tracking requires two stepper motors to position the heliostat in the unique position ensuring that the solar flux is always being focused onto the solar absorber as the sun traces its trajectory for the average 10-hour period sunlight day! In practice a maximum of two-axis or dual tracking is adequate. The east-west can be taken as the x-axis and the north-sky-south as the y-axis i.e. a two dimensional vector.

According to W.H. Traugott (1990), ‘mirror surface 55m^2 to 65m^2 up to 12 heliostats will be controlled by group controllers which are largely independent from the central field computer.’

Drawing of reflector and target

$$L = (2 \cdot E) / 3 - T = +60^{\circ}$$

Where

L=Ideal reflector angle, catching the most sun possible while reflecting it all on the target.

E=Sun’s elevation

T=Angle of target

The best angle for shading are also surprising.

1.3 REALIZATION OF A SOLAR TRACKER

To develop a solar tracker that is dual-axis there has to be:-

- (a) A mechanical mechanism which allows east-west 180^0 rotation and another mechanism for facilitating north-south 180^0 rotation above each other.
- (b) An electrically and electronically controlled motor or a pneumatic or hydraulic actuator.
- (c) Motor control board
- (d) A computer and an Arduino controller together with a circuit for motor control.

According to W.H. Traugott (1990), mirror surface 55m^2 to 65m^2 up to 12 heliostats will be controlled by group controllers which are largely independent from the central field computer.

The mechanical mechanisms include (1) 2 centrally rotatable rectangles about a central spindle on top of each other (2) 2 rotatable spindles one about a tube and another about a rectangle. Among others

3.0 TRACKING ACCURACY

So as to track the solar trajectory, we need knowledge about Sensors and instrumentation. According to D.N. Pandey (2018), **instrumentation** is the study of detection, acquisition, control and analysis in all areas of science and technology. Instrumentation or sensors which detect and measure variables like solar insolation is essential for the control of this variable.

According to Pandey (2018), a **Sensor**: is an element which detects a change in energy that is inputted to generate a change in another but having same energy type or form.

A Transducer: is a device which transforms one form of energy to another using transduction principle e.g. to provide an electrical output in response to a specific measurement from another form of energy e.g. thermal, mechanical, chemical.

According to W.H. Traugott (1990), “Tracking accuracy is the angular deviation of the centroid of the reflected beam from a reference ‘aim-point’. The resultant angular error comprises two components, horizontal and vertical.’ The measurement system consists primarily of a target (receiver) and data acquisition system.’

A pyrheliometer: is a device for measuring direct sunlight’s flux at incidence that is normal. The device is normally bound to an equatorial mount that is electrically driven that tracks the sun (H.P. Garg and S.N. Garg (1991))

A pyrheliometer measures only beam radiation. Diffuse radiation cannot be measured with this instrument.

These motors or hydraulic actuators will normally be controlled by a computer and an Arduino controller programmed in C programming language or in machine language.

Photodiodes and or heat-sensitive resistors (light-dependent resistor-LDR) may also be used for sensing the sun’s trajectory within the sky and giving signals to the controlling computer or microcontroller for ultimately commanding the heliostats to face a particular position.

Tracking can be based on signals from (a)the passage of time or (b)amount of solar insolation as sensed by sensors such as a photodiode, heat-sensitive resistor (light-dependent resistor-LDR) or pyrheliometer.

According to Alternative Energy in Power Electronics report (2015), One-axis tracker is better at cost-effectiveness than Two axis tracker. Awasthi et al. (2020) highlights that dual axis tracking has higher efficiency and superior performance than single axis tracking.

Tracking methods can also be classified as manually controlled trackers or technologically control known as automatic trackers

Manually controlled trackers are whereby heliostats are adjusted to meet the two constraints mentioned above by human labor as the sun travels in the sky from East

to West. Technologically controlled or automatic heliostat trackers adjust the heliostats position to meet the two constraints with minimum or no human intervention as the sun moves from east to west in the sky.

There are pneumatically or hydraulically actuated trackers and electric motor and gearing actuated tracker! The actuators will be receiving commands from Arduino controllers or computers in response to signals from sensors such as (1) photo resistors, photodiodes or light dependent resistors(LDRs), passage of time, pyrhelimeter or smaller solar panels (3) 4 smaller photo-sensors like solar panels behind the solar panels with two pair smaller solar panels connected to an electric motor in opposite polarity (one pair for east-west tracking and another pair North-sky-south tracking) for dual axis tracking.

According to B.P. Gupta and W.H. Traugott (1990), **Beam quality** is the angle of deviation that exists between the actual surface's normal and the reference normal. This deviation at any point on the surface is assumed to establish a circular normal distribution.

Cameras and Artificial intelligence can be used to track heliostats.

Al-Rousan et al. (2020) describes several types of controllers such as microprocessors, algorithms, artificial intelligence methods, electronic circuits, technical methods or motors which could be used. Controllers based on fuzzy logic have been used. Month, day, Time changes were employed as inputs to foretell the optimal orientation and tilt angles. Sensors of light were employed to get values of light intensity including employing them as input variables to forecast the motion angle and servo-motor direction. Neural networks and Fuzzy logic principles can be used in combination to effectively track the sun's position.

4.0 CONTROL SYSTEMS

According to A.H. Morton(1980), where accurate and precise control of some desired quantity is required (e.g. temperature of TES tank or receiver/thermal absorber, flowrate of working fluid into the turbine, speed of the prime mover or motor and or current output from a CSP generator) it is necessary to compare the controlled quantity with some reference value, and to adjust the system in such a

way that any disparity existing between desired output (current from a light-dependent resistor (LDR) i.e. a photodiode or small solar panel sensors being actuated by solar insolation) and actual output (current transformer(CT) output being fed from the generator output current) is reduced. This is called **closed-loop-control system**, since the processes of measurement, comparison (by a differential amplifier) with the desired value and subsequent correction (by the controller through the motor if an error is found) may be thought of as forming a closed loop. This may be defined as an error actuated control system with power amplification.

The control system resulting from the error signal may be simply proportional to the error (proportional control) but may also include terms dependent on the time integral of the error(reset) or the time derivative of the error (rate action), or both (three term control).

Control systems e.g. for heliostats may be pneumatically, hydraulically or electrically operated or actuated.

When accurate control is not required, a simple open-loop system may be employed, where there is no feedback of information from the output to the input e.g. a fuse.

For comparing output to reference input, we may use a differential amplifier which feeds into an PLC controlling the electric motor which positions the heliostat. The differential amplifier may implement negative feedback.

5.0 COMMUNICATION LINKS

Communication links will be required to link, connect and provide path for control signals from sensors to Arduino controllers and from controllers to actuators such as electric motors and or hydraulic or pneumatic actuators. These links maybe copper wire, fibre optic or wireless(radio) links depending on practicality. Communication theory hence becomes also relevant for advanced solar tracker design.

SIGNAL CONDITIONING

The generated signal may need attenuation, amplification, modulation or transformation in order to be compatible with the needs of the system in a process called signal conditioning.

SOLAR TRACKING

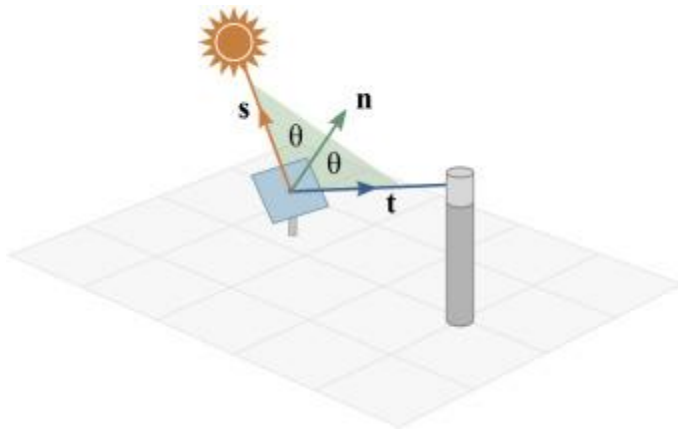


Image from a paper by Grigoriev, Milidonis and Blanco (2020)

Figure 43

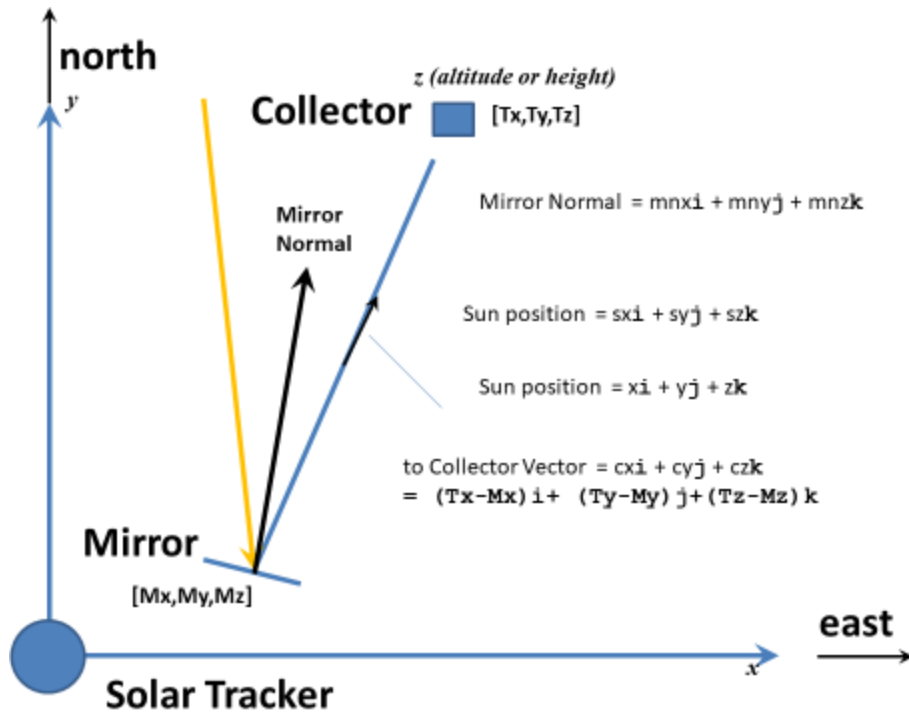


Figure 44

The normal to the heliostat vector ($\underline{n}$ in black) and the vector of the sun's direction ($\underline{s}$ in yellow) varies while the receiver vector's direction ($\underline{r}$ in blue) remains constant. The incident and the reflected angle must remain equal.

$\underline{n} = f(\underline{s}, \underline{r})$ where $\underline{r}$ the receiver direction is a constant and $\underline{s}$ the sun direction is a variable. If we can derive a relationship connecting $\underline{n}$ and the variables $\underline{s}$ and $\underline{r}$, then $\underline{n}$ is the control signal for the heliostat position.

$$\underline{r} \cos \theta_2(t) = \underline{s} \operatorname{cosec} \theta_1(t) \quad \text{Equation 1.1}$$

$$\theta_2(t) = \theta_1(t) \quad \text{Equation 1.2}$$

$$\operatorname{cosec} = 1/\cos$$

$$r \cos^2 \theta = s$$

$$\cos^2 \theta = s/r$$

$$\cos\theta = \sqrt{s/r}$$

$$\theta = \cos^{-1} \sqrt{s/r}$$

$s = 180^\circ / 12 \times 60 = 0.25^\circ$ per minute in the East-West direction.

$s = 0.25^\circ \times \text{time (in minutes from 06:00 to 18:00)}$

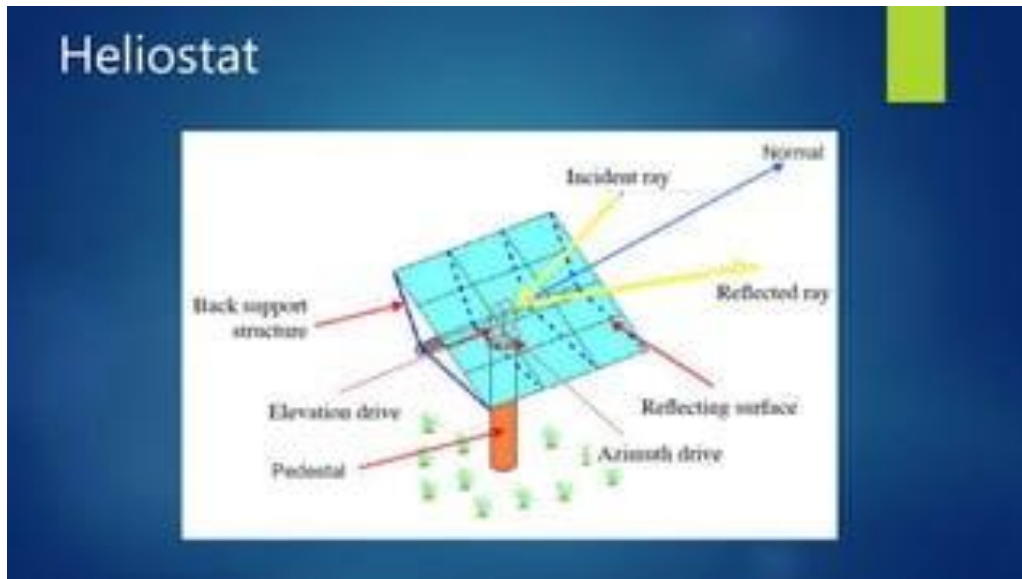


Figure 45

The other method proposed by the authors of this paper is to approximate that the sun moves only from east to West (i.e. 180°) per day meaning that each heliostat moves half this value i.e. 90° per day. We calculate 2 set points for each mirror where we put 2 limit switches for the heliostat controlling motors. We write a 'C' program for controlling each electric motor for each heliostat. The heliostat normal must always bisect the sun-heliostat-absorber angle. If we take a hypothetical heliostat 'r' meters from the tower and assume the sun's incident angle=reflected

angle to receiver= Θ . If we assume the tower's height='h'. The angle that the tower makes to the heliostat relative to the horizontal of the mirror= $(90-\Theta)$. If we assume that the angle that the heliostat makes with the ground = ϕ

$\tan(90-\Theta+\phi)=\frac{h}{r}$ where Θ and ϕ are variables and 'h' and 'r' are constants for each heliostat

6.0 Installation of Heliostats

In Southern Hemisphere the sun is slightly north and in Northern hemisphere slightly south in its east-west trajectory within the sky.

Challenges for future research includes researching on identifying the best and optimal tracking method for Photovoltaic (P.V.) power plants amongst the 4 methods mentioned in this paper i.e. (1) use of astronomical equations (2) the shadow method and (3) approximating that the sun moves only 180° east-west and each heliostat moves 90° per day. The P.V tracking methods may be used to determine the sun vector and further used to calculate the sun-heliostat-absorber bisector for positioning the normal of the heliostat for Central Receiver Tower power plants. The P.V tracking method to identify sun's position at one point is broadcasted to all mirrors to give the sun vector. Since the receiver vector is constant, the bisector of the sun-heliostat-receiver angle can be computed for each heliostat by computers.

Mpadi et al(2019) posits that chronological trackers employ astronomical and geographical information and data to calculate the vectorial trajectory of the sun for each day and season with the help of mathematical formulae and algorithm.

Time-Dependent Tracking Methodology

The sun has an east-west daily trajectory and a yearly south-vertical- north seasonal variation necessitating dual axis tracking for more accurate tracking and enhanced plant efficiency.

The assumption is that on the summer solstice i.e. December 22, the sun rises exactly from the east passing vertically above us and sets in exactly the west i.e. moves 180° . Each heliostat will move half the angle i.e. 90° from its set point at 06:00 where

it must always bisect the sun-heliostat-absorber angle from 06:00 to 18:00 p.m. This means $180/12$ i.e. the sun moves 15° and the heliostat 7.5° per hour in the East-West direction

According to Yilmaz et al. (2014), each mirror and therefore heliostat has unique target angle to the receiver or facing angle and different target distance. Each mirror will therefore have a different December 22, 06:00 a.m. set point where the heliostat will have to bisect the sun-heliostat-absorber angle equally. (Summer Solstice). The sun moves 180° east-west and the heliostat moves 90° east-west from 06:00 a.m. to 18:00 pm when it hits a limit switch and the mirror rotates back west-east 90° . it rests for 12 Hours and starts the cycle again. There will be an east limit switch and a west limit switch separated 90° apart on the gears of the motor controlling the heliostat. There will also be north-south 2 limit switches to mark the summer solstice and winter solstice positions. The sun moves 45° in 6 months meaning $45/6 = 7.5^{\circ}$ per month and the heliostat moves 3.75° in per month. Rotating speed of each heliostat north-south $= 7.5^{\circ}$ per month.

We can find the degrees north-sky-south seasonal movement of the sun at Kadoma or any place from Jaloxia (2025)'s sun-path diagrams. In 6 months December to June the sun will move north-south directions with degrees as shown in the sun-path diagram and we can therefore calculate its speed. From the sun-path diagram the sun moves 45° north-sky vertical in 6 months meaning 7.5° per month. In the next 6 months it moves 45 degrees from north towards vertical position i.e. 7.5° per month.

The subject of control systems is also essential in understanding, comprehending and mastering the design of solar tracking intelligence. Limit switches at the extreme east and extreme west are needed to signal end of day (sunset) and beginning of day (sunrise). Another set of limit switches to signal summer solstice and winter solstice (vertical and 45° north(sky)-Southern Hemisphere or Vertical-South-Northern hemisphere).

Contribution to worldly body of Knowledge

Solar tracking in Central Receiver Tower Power Plants is a gray area in Literature reviewed. Since the sun is very far away from earth, the sun's vector is approximately the same for each heliostat. If sensors together with digital inclinometer which communicates with the computer with the absorber vector for each heliostat are installed at one central position near the tower, the normal for each heliostat can be calculated from the sun vector and absorber vector. It implies that the GPS coordinates of each heliostat and the receiver must be known. This means methods for tracking for P.V. can be used to find the sun's vector for Central Receiver Tower power plants. The heliostat normal vector is half the sum of absorber vector plus the sun vector from North to South and East to West.

Areas for Future Research

There is need to continue researching on how to further increase the tracking accuracy of the solar trackers. The cost of the trackers need to keep on being reduced and this requires materials and mechanism research.

KEY ASSUMPTIONS MADE

- (1) The heliostat mirrors are always focusing light onto the receiver. In practice there is spillage and the tracker may develop faults.
- (2) Wind forces onto the tracker support are always constant. In practice wind varies with seasons with August having the largest winds

7.0 Conclusions

Solar tracking for CRTPs is far more complicated than solar tracking for photovoltaic plants. The heliostat normal must always bisect the sun-mirror-absorber angle throughout the day for CRTPs! If the sun moves $2\theta^\circ$ east-west or north-south, the heliostat bisector must move θ° east-west or north-south respectively for accurate tracking. Astronomical equations, the passage of time or

sensors need to be used to identify the sun vector for PVs. For rough estimates we may consider the sun to move 180° East-West and each mirror has to move 90° from initial setting throughout the day from sunrise to sunset for single axis tracking. There are 3 tracking methodologies for P.V. power plants (1) one which uses sensors (2) the length and shadow method and (3) one which uses time and astronomical equations to find the sun vector. The determined sun vector can be broadcasted to a computer controlling all heliostats and together with the absorber vector can be used to calculate the sun-heliostat-receiver bisector for CRTPPs. Modern systems use hybrid methods which combine sensors and astronomical equations for more accurate and robust tracking.

3.5 SUN TRACKING MECHANISM

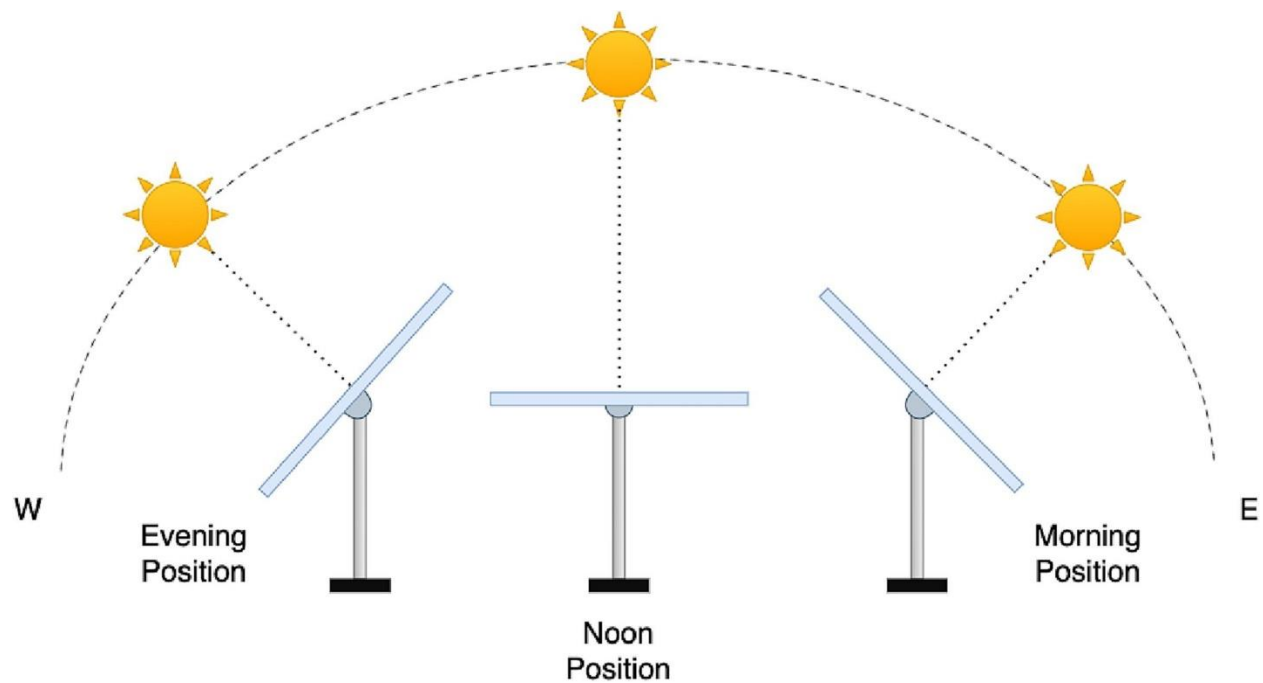


Figure 46

INTRODUCTION

Zimbabwean Situation

Zimbabwe is a country experiencing critical power shortages as a result of droughts and frequent breakdown and maintenance of thermal power stations such as Hwange. Compounding this problem is the fact that there is world and a United Nations pressure to close down coal power stations such as Hwange Power Station that is the largest power plant in Zimbabwe. Zimbabwe is endowed with a lot of coal giving authorities no option but to expand Hwange power station while going through the learning curve of constructing favored Renewables like Wind generation, solar, geothermal generation and non-renewable generation like Nuclear. In partnership with countries like Mozambique Zimbabwe can also explore opportunities in tidal generation and wave generation

This section explores possible solar tracking mechanisms. Four MECHANISMS were identified (a) thermomechanical and electrical e.g. (1) Pneumatic solar tracking actuators (2) hydraulically driven solar tracker where the expansion of a low temperature boiling point liquid or a liquid with high expansivity exposed to sunlight drives the rotation of the opposite side of a solar panel.

(3) electrical powering gear wheels driven by stepper motors, linear motors, d.c. motors or servo-motors being controlled by a 'C' language programme written in the Arduino Uno microcontroller and (4) hybrid trackers

MAIN NARRATIVE

Pneumatic solar trackers employ air which is compressed to align the solar panels' orientation for maximum collection of the amount of solar flux they receive. Solar panels themselves power a small compressor that supplies the air that is stored and contained in the tank and distributed via tubes. This compressor is connected via tubes to actuators that contract and expand and distribute air using pistons through the above tubes. The light dependent resistors or photodiodes sensors mounted under the panel detect the solar vector or sun's position, monitoring alterations in the intensity of light. Differences in exposure to light between east and west LDRs is detected by a control unit normally Arduino Uno which processes this data and computes the ideal angle that gives maximum solar capture and regulates the flow of air to the actuators. The panels thus continuously face the sun and thereby optimizing outputted power and energy.



Figure 47



Figure 48

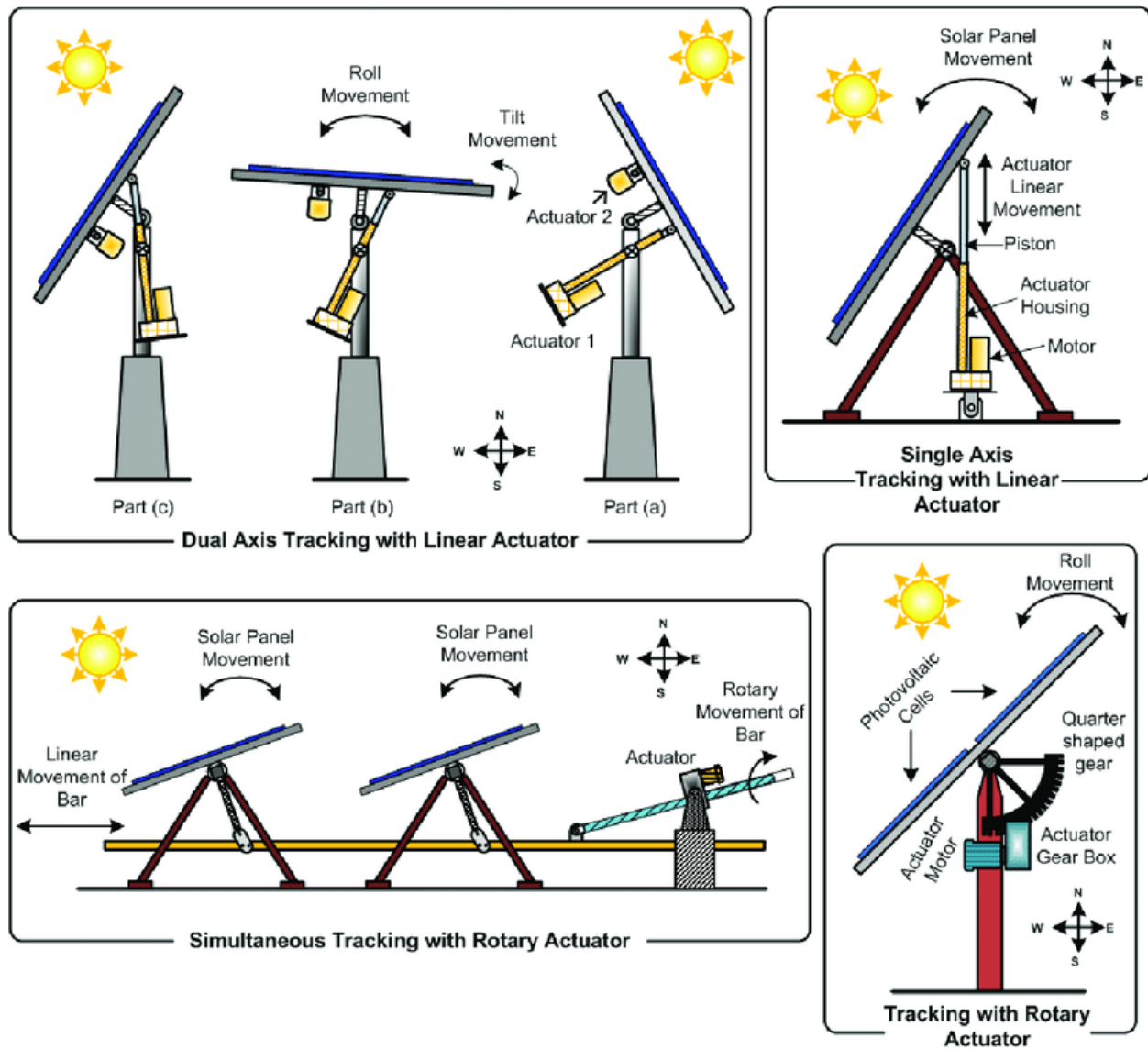


Figure 49

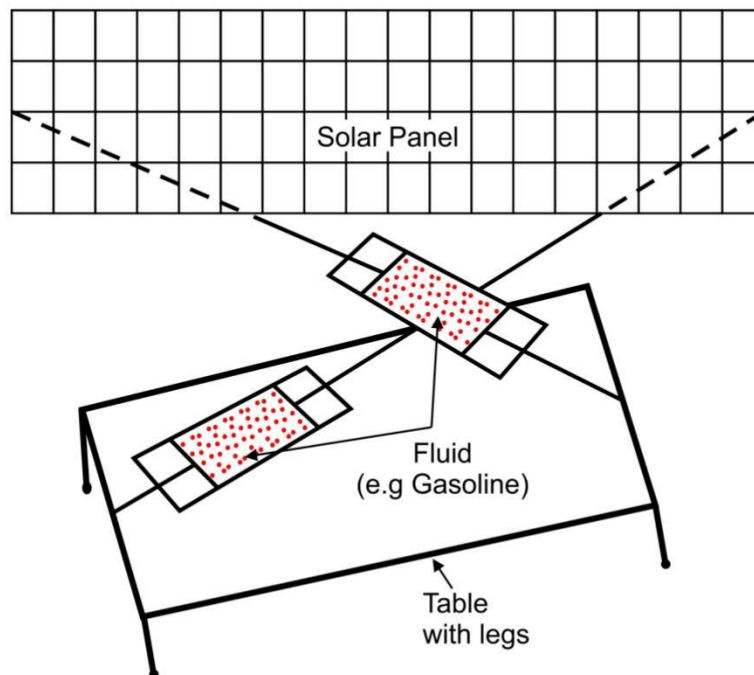
According to Abdul-Hussein et. al (2024), the advantages of pneumatic solar trackers are as follows: -

1. Less costly
2. Less maintenance
3. Longer operating life times
4. Easier to operate than electrical
5. Lower costs of production

6. Lower risks of contamination than hydraulic trackers
7. Not much affected by fluctuations in external temperature
8. More reliable compared to hydraulic trackers
9. Cleaner than hydraulic trackers
10. NEED FEWER MATERIAL to manufacture than the other type of sun trackers
11. Environmentally friendly than hydraulic trackers

Hydraulic Solar Tracking Mechanisms

HYDRAULIC / PNEUMATIC SOLAR TRACKER



NB: Any gas or liquid with high thermal expansivity can be used as the actuating fluid.

Figure 50

Butane, Gasoline, acetone, formaldehyde and glycerin liquids are used either because of low boiling points and or high thermal expansivity. BENZENE although with high expansivity but was not recommended because of its toxicity. When the sun is exposed to the Eastern casing or tube containing gasoline or butane, it expands pushing the panel's opposite side thereby forcing the solar panel to spin in a

clockwise direction until both tubes are within the shadow or equally illuminated. If the sun is exposed to the tube on the West, the gasoline expands forcing the panel and opposite side to spin in the direction that is anti-clockwise until both tubes are within the shadow of the panel or equally illuminated. This way the rays of the sun are always normal or at 90° to the panel's surface.

Advantages of Electrical solar trackers

More efficient than other trackers. Do not employ external energy supplies or same solar panels for tracking

- Complexity is less
- Need less maintenance
- Less constrained by size compared to other actuators

Hussein (2024), says there are very few literatures on pneumatic solar trackers and hence the project decided to design the electrical trackers using Light Dependent Resistors.

ELECTRICALLY OPERATED MECHANISM



Figure 51

The purpose of this part of the project is to give details and information about designing a Two-axis sun tracker's mechanism which may be for photovoltaic power plants such as the one at Nyabira Centragrid Power station in ZIMBABWE or for a Central Receiver Tower Power Plant for strategically capturing and concentrating solar flux onto a stationary Solar absorber which is also called 'a heat capturing element fixed on top of a Tower centrally positioned in the power plant which may be 240 m high for actual plants but far smaller for prototypes. The dual tracker mechanism has a daily East-West rotating mechanism and a seasonal North-South rotating mechanism and hence two round gear wheels above.

Introduction

Solar tracking is the process of following of the direction of the sun by a solar panel or solar array mounted on top of a semi-spinning or semi-rotating mechanism around a pivot of the sun's position and direction in relation to a given location on the surface of the earth such that the rays of the sun will always fall perpendicularly to

the surface of the solar panel. This maximizes solar collection and hence solar generation

In Central Receiver Tower Power Plants, there is need for solar flux redirecting, re-focusing and concentration by heliostat mirrors onto a stationary solar absorber or receiver on top of a very tall central tower as the sun moves every day East-West and North-South seasonally.

SOLAR TRACKING EXPLOITING GEAR WHEELS AND STEPPER MOTORS

The East=West and North-South rotating gears movement is similar or identical to astronomical clock. The spinning speed in gears per minute or degrees per minute is predefined. Each of the gear circles spin for 180 degrees in 12 hours clockwise and 180 degrees in 12 hours anticlockwise and repeats the cycle. The forth and back movements are repeated as many times as possible

THE CLOCKWISE SPINNING AND ANTI-CLOCKWISE SPINNING can be caused by two methods

- (1) Chronological (clocklike movements- semi-rotation movements) the input signal is time of day or time interval from set time
- (2) With sensors e.g. light or shadow on different Light dependent resistors or photodiodes which gives signals to an Arduino controller which energizes the motor control circuits. The input signal is electricity from light dependent resistors or photodiodes.

COMPONENTS OF ACTIVE TRACKERS (According to Elsayed et.al (2021))

- (1) Mechanical support and mountings
- (2) Mechanical power transmission components and gearwheels
- (3) Source of electricity
- (4) Arduino controller
- (5) 'C' Control computer programme
- (6) Electric motors e.g, d.c. motors and or stepper motors
- (7) Electronic circuits
- (8) Gear boxes

- (9) Four quadrant Light Dependent Resistors(LDRs) or photodiodes used so as to sense the sun's direction from the solar panel (resistance imbalance due to unequal or different exposure to light of the LDRs) (Alsayed et. al (2021)

D.C. motors have high torque to rotate the mechanical gear wheels on which the solar panels are mounted. Stepper motors ensure smooth spin or rotation. The gear wheel rotation or spin signal originates from the LDRs via Arduino programme to d.c. and stepper motors

Main Text

Mechanical systems for tracking the sun operates in a principle identical or similar to a mechanical clock. An operating system of gear wheels and gear trains helped by potential load or d.c. motor or stepper motor torque is used to spin or rotate the sun concentrator or solar trapping in order to focus it in the Power Tower Power stations in response to the solar motion from sunrise to sunset –normally about 06:00 a.m to 18:00 p.m.

Solar energy possess capacity to satisfy all the global village's power requirements in future Argarwal (2000). Solar tracking enhances solar collection efficiency by solar panels in Photovoltaic (P.V.) power plants and solar trapping and focusing by heliostat mirrors in Central Receiver Tower Power Plants according to Argarwal (2000). This improves, enhance and optimized electricity generation capacity in either P.V. power plants or Central Receiver Tower Power Plants. In solar tracking especially dual axis tracking in P.V. power plants, the solar rays must always fall onto the solar panel at 90° from morning to sunset.

This ensures that almost all sunlight or solar flux falls on the targeted area e.g. of solar panels in P.V. power plants or heliostat mirrors in Central Receiver Tower Power Plants.

The mechanism for sun tracking is rotated according to movements of sun to meet conditions above e.g., solar irradiance must fall 90° to the solar panel surface in P.V. power plants and (2) the heliostat mirror normal must bisect the sun vector

angle and receiver angle measured from the heliostat mirror surface for Central Receiver Tower power plants. The bisector angle is also half of the solar vector (sun's direction) and solar absorber vector (or receiver direction) from the heliostat mirror measured from horizontal East from the heliostat. The incidence angle of the solar flux on the heliostat mirror must be always equal to reflection angle of the trapped solar insolation of sunlight to the absorber on the heliostat mirror.



Figure 52

There are 2 wheel gears in the above diagram-top one for East-West daily semi-spinning and semi-rotation and another bottom gear wheel for North-South semi-spinning or semi-rotation for sun seasonal direction change. The gear wheels are rotated by stepper motors driven by an Arduino controller's programme.

The gear wheel teeth apart from being an actuator for enabling rotation, they also facilitate locking of the platform to be semi-rotated back and forth and the gear wheel so that rotational movements are accurately determined, quantified and are done as intended by the mechanical mechanism designer. The top gear wheel is for EAST-West movement since this occurs more frequently on a daily basis and the bottom gear wheel for North-South seasonal movements since these are less frequent. A lot of energy is saved this way as the daily movements excludes a lot of the bottom weight in its daily trajectory.

The mechanism of gears is employed to guarantee that the mechanism's rotation is compatible to the velocity of the motion of the sun from sunrise to noon to

sunset(semi-circle) meeting the conditions specified above depending on whether its P.V. or Central Receiver Tower Power Plants. A semi-circle has 180° . This means the East-West gear train must ensure that the solar panel rotates through 180° in 12 hours (06:00 a.m. to 18:00 p.m. or from sunset to sunrise). So the East-West mechanism holding the solar panel in P.V. power plants moves $\frac{180}{12} = 15^{\circ}$ per hour or $\frac{15}{60} = 0.25^{\circ}$ per minute for solar P.V.

For a 24 teeth gear wheel, $360^{\circ} = 24 \times 0.25^{\circ} = 3.75$ teeth per minute.

For the dual tracker, if we use a 24 teeth gear wheel- the East West daily sun tracking gear wheels, it means

24 teeth = 360° rotation

12 teeth = 180° rotation

6 teeth = 90° rotation

3 teeth = 45° rotation

We are interested in the gear wheel turning 12 teeth (i.e. 180°) BACK AND FORTH in 24 hours for Photovoltaic Power Plants where the solar rays must always be perpendicular to the surface of the solar panel. For Power Tower energy stations, the heliostat mirrors must have its controlling gear wheel turn 6 gears (i.e. 90°) back and forth from the East set position every 24 hours.

This is not true for the seasonal controlling gear wheel which is the other or bottom gear wheel in the tracking mechanism diagram. There will also be north--south 2 limit switches to mark the summer solstice and winter solstice positions. The sun moves 45° in 6 months (i.e. 3 gear rotation) meaning $45/6 = 7.5^{\circ}$ per month and the heliostat moves 3.75° in per month. Rotating speed of each heliostat north-south = 7.5° (0.5 gear rotation) per month.

We can find the degrees north-sky-south seasonal movement of the sun at Kadoma or any place from the sun-path diagrams on Jaloxa (2025) website. In 6 months

December to June the sun will move north--south directions with degrees as shown in the sun-path diagram and we can therefore calculate its speed. From the sun-path diagram the sun moves 45° north-sky vertical in 6 months meaning 7.5° per month. In the next 6 months it moves 45 degrees from north towards vertical position i.e. 7.5° per month.

After the gear train or solar panel holder rotates for 12 hours it must hit a limit switch and return to horizontal EAST where it started in the morning. It must remain stationary for 12 hrs and then start the movement again. A controlling programme e.g. 'C' language programmed in the Arduino controller controlling the stepper motor and or d.c. motor achieves this through motor torque for P.V. Power Plants.

For heliostat solar capture and focuser, the situation is a bit different. Take for example a heliostat just underneath the tower at sunrise the sun or solar vector = 0° measured from that heliostat. The solar absorber vector from that heliostat mirror is 90° measured from standard horizontal East. half the two angles = $\frac{0+90}{2} = 45^{\circ}$. The normal of that heliostat mirror must be 45° from horizontal East. By the same reasoning at sunset the mirror will be 45° FROM Horizontal West or $(90^{\circ} + 45^{\circ}) = 135^{\circ}$ from Horizontal East. THE HELIOSTAT will move $45^{\circ} + 45^{\circ} = 90^{\circ}$ in 12 hours. This means the heliostat mirror must be rotated $(\frac{90}{12} = 7.5^{\circ})$ per hour. This also translates to $\frac{7.5}{60} = 0.125$ per minute depending on how sensitive you want the East-West tracking mechanism holding the heliostat mirror to rotate

This means for each heliostat mirror, we have to establish the morning bisector angle and sunset bisector angle as done above and put limit switches for these two positions to signal end points. After rotating from morning position to sunset position, the mechanism returns back to initial sunrise position, rests in that position for 12 Hours and restart the morning, noon and sunset position and resets.

A 'C' programming language to be written in Arduino to control

Time-Dependent Tracking Methodology

The sun has an east-west daily trajectory and a yearly south-vertical- north seasonal variation necessitating dual axis tracking for more accurate tracking and enhanced plant efficiency.

The assumption is that on the summer solstice i.e. December 22, the sun emerges and rise from exactly the east passing vertically above us and sets in exactly the west i.e. moves 180° . Each heliostat will move half the angle i.e. 90° from its set point at 06:00 where it must always bisect the sun-heliostat-absorber angle from 06:00 to 18:00 p.m. This means $180/12$ i.e. the sun moves 15° and the heliostat 7.5° per hour.in the East-West direction

According to Yilmaz et al(2014), each mirror and therefore heliostat has unique target angle to the receiver or facing angle and different target distance. Each mirror will therefore have a different December 22, 06:00 a.m. set point where the heliostat will have to bisect the sun-heliostat-absorber angle equally. (Summer Solstice). The sun moves 180° east-west and the heliostat moves 90° east-west from 06:00 a.m. to 18:00 pm when it heat a limit switch and the mirror rotates back west-east 90° . it rests for 12 Hours and starts the cycle again. There will be at east limit switch and a west limit switch separated 90° apart on the gears of the motor controlling the heliostat. There will also be north--south 2 limit switches to mark the summer solstice and winter solstice positions. The sun moves 45° in 6 months meaning $45/6 = 7.5^{\circ}$ per month and the heliostat moves 7.5° in per month. Rotating speed of each heliostat north-south $= 7.5^{\circ}$ per month.

We can find the degrees north-sky-south seasonal movement of the sun at Kadoma or any place from the sun-path diagrams on Jaloxa (2025) website. In 6 months December to June the sun will move north--south directions with degrees as shown in the sun-path diagram and we can therefore calculate its speed. From the sun-path diagram the sun moves 45° north-sky vertical in 6 months meaning 7.5° per month. In the next 6 months it moves 45 degrees from north towards vertical position i.e. 7.5° per month.

The subject of control systems is also essential in understanding, comprehending and mastering the design of solar tracking intelligence. Limit switches at the extreme east and extreme west are needed to signal end of day(sunset) and beginning of day

(sunrise). Another set of limit switches to signal summer solstice and winter solstice (vertical and 45° north(sky)-Southern Hemisphere or Vertical-South-Northern hemisphere.

‘C’ PROGRAMME

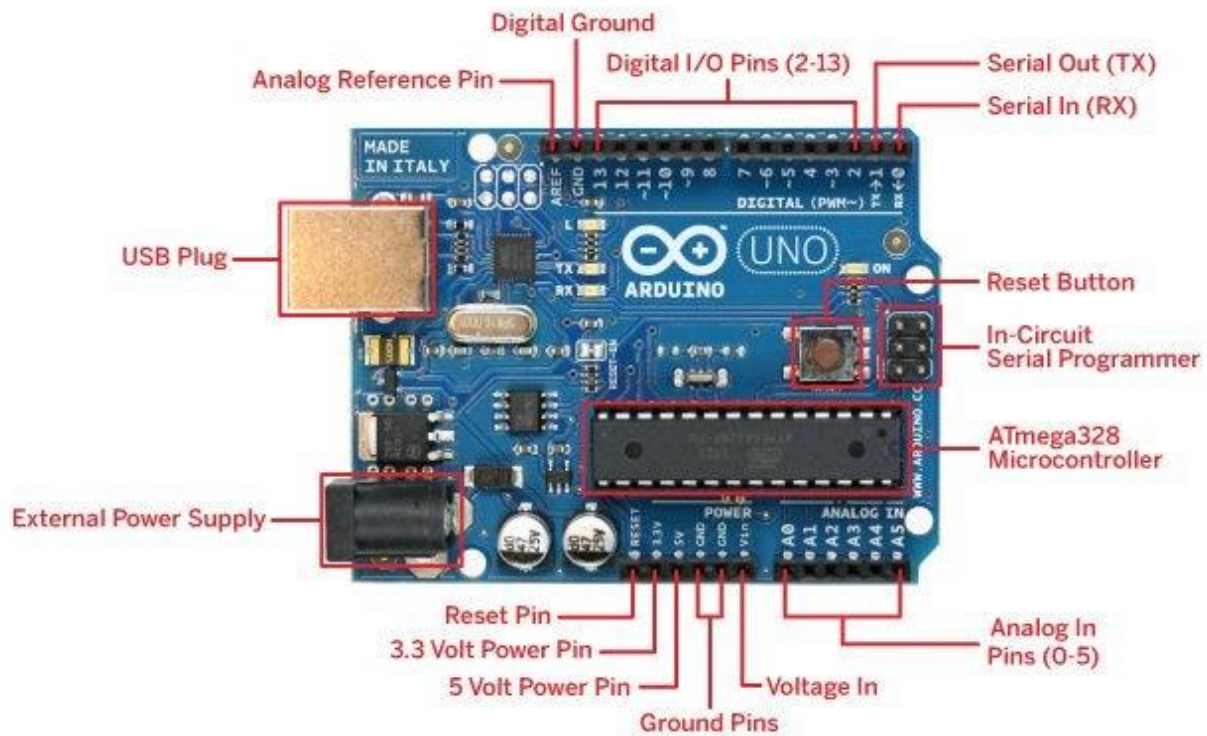


Figure 53

SOLAR TRACKING USING LDRs

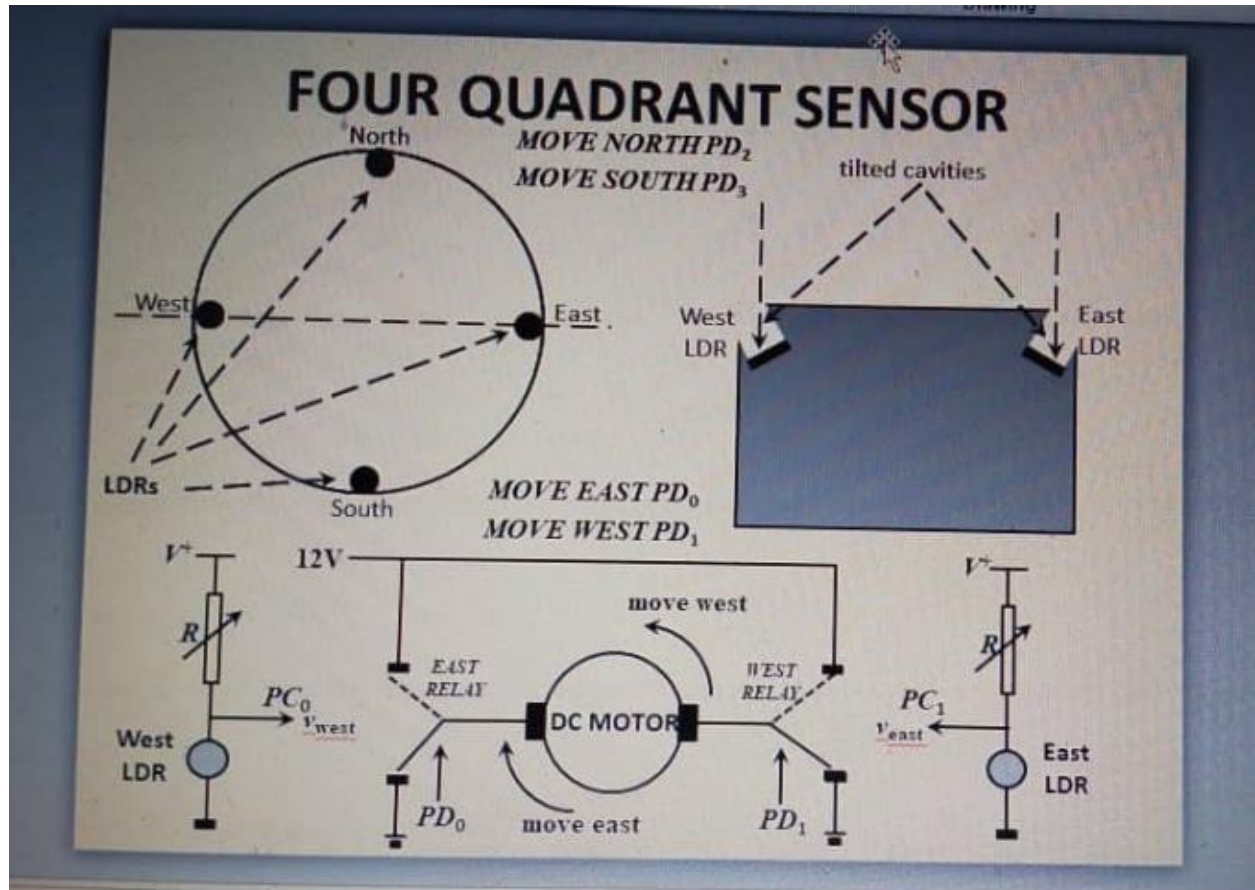


Figure 54

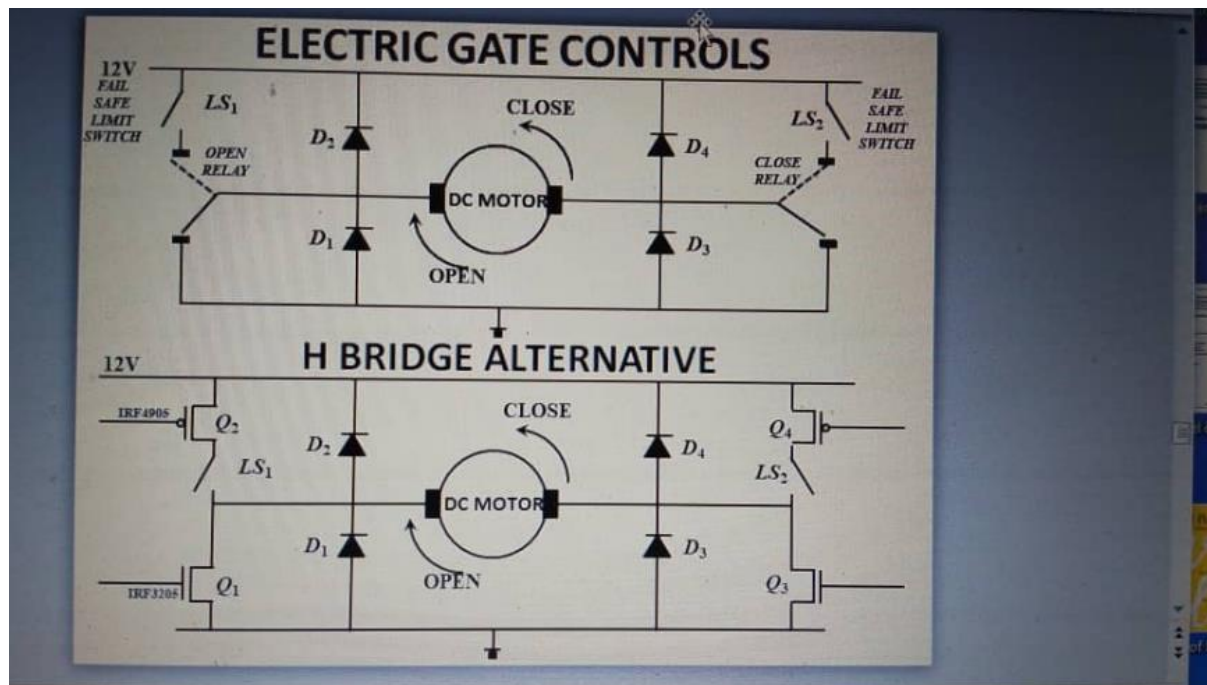


Figure 55

This technology employs mechanical gears and electrical drives to position the solar panels surface at 90° to the sun's rays. It exploits sensors such as Light Dependent Resistors (LDRs), stepper motors and Arduino microcontroller for more efficient and accurate tracking. When the solar panel is not properly aligned, with respect to the sun's rays, different solar flux illumination is experienced by the LDRs on opposite sides of the panel and forms a differential signal that is then exploited by the comparator or an Arduino controller to quantify the needed movement and direction. The needed signal is then transmitted to the stepper motors to work in accordance with the required action. The process ends when the 2 pairs of LDRs on opposite sides of the panel receive equal illumination. This indicates that the module of the PV is correctly oriented with solar rays or flux.

TWO AXIS SOLAR TRACKING

- The amount of solar flux collected can be enhanced by solar tracking.
- The sun's radiation must always fall at 90° to the solar panel's surface for maximum generation because of the $\cos \theta$ factor.
- The panel must move East-West daily to track sun's daily trajectory.
- The North-South seasonal movements of the panel are needed for seasonal sun position variation.
- We need 2 d.c motors
- Quadrant sensors with 4 Resistors that Depend on Light (LDRs) are needed.
- Solar will be automatically tracked by the 'control programme'.

OPERATIONAL LOGIC

- In the dark, the LDRs have infinity resistance.
- In direct sunlight the impedance of the LDR drops to 300 ohms.
- When the solar rays are 90° to the surface of the panel, East and West LDRs possess equal resistance.
- Analogue inputs are fed by the East and West voltages.
- When the sun's movement is to the West then $V_{west} < V_{east}$.
- If there is a difference $V_{east} - V_{west} > V_{sensitivity}$ move Westwards
- The westwards movement continues until difference $V_{east} - V_{west} \leq 0$
- 2 relays are needed by each d.c. motor in order to move either direction and will usually employ a gearbox.
- The east-west and then North-South movement is continually monitored by the tracking programme and corrective action is taken.

Solar TRACKING PROGRAMME

```
void east_west() {  
  word east_ldr, west_ldr, sensitivity;  
  east_ldr = analogRead(EAST_LDR);  
  west_ldr = analogRead(WEST_LDR);  
  sensitivity = analogRead(SENSITIVITY);  
  if (abs(east_ldr - west_ldr) > sensitivity) {  
    if (east_ldr > west_ldr) {  
      digitalWrite(MOVE_WEST, HIGH);  
      do  
      {  
        east_ldr = analogRead(EAST_LDR);  
        west_ldr = analogRead(WEST_LDR);  
        sensitivity = analogRead(SENSITIVITY);  
        while (east_ldr - west_ldr > 0);  
        digitalWrite(MOVE_WEST, LOW);  
      } else {
```

```
    } else {  
        digitalWrite(MOVE_EAST,HIGH);  
        do  
            east_ldr = analogRead(EAST_LDR);  
            west_ldr = analogRead(WEST_LDR);  
            sensitivity=analogRead(SENSITIVITY);  
            while (west_ldr - east_ldr > 0);  
            digitalWrite(MOVE_EAST,LOW);  
        }  
    }  
}
```

The void function north_south() is similar

```
void loop() { // this continuously tracks the sun  
    east-west();  
    north_south();  
}
```

STEPPER MOTOR PROGRAM

```
#define C1P 7
#define C1N 6
#define C2P 5
#define C2N 4
int torque = 3;
int gap = 20;
enum states {idle, state_0, state_1, state_2, state_3};
enum states stepper_state = idle;

void clockWise (int notch count) {
    int count_notches;
    for (count_notches = 0; count_notches < notch_count;
        count_notches++) {
        switch (stepper_state) {
            case idle : digitalWrite(C1P,HIGH);
                        stepper_state = state_0;
                        delay(torque);
                        digitalWrite(C1P,LOW);
                        break;
            case state_0 : digitalWrite(C2P,HIGH);
                        stepper_state = state_1;
                        delay(torque);
                        digitalWrite(C2P,LOW);
                        break;
            case state_1 : digitalWrite(C1N,HIGH);
                        stepper_state = state_2;
                        delay(torque);
                        digitalWrite(C1N,LOW);
                        break;
            case state_2 : digitalWrite(C2N,HIGH);
                        stepper_state = state_3;
                        delay(torque);
                        digitalWrite(C2N,LOW);
                        break;
            case state_3 : digitalWrite(C1P,HIGH);
                        stepper_state = state_0;
                        delay(torque);
                        digitalWrite(C1P,LOW);
```



```

        break;
    }
    delayMicroseconds(gap);
}
}

void setup() {
    Serial.begin(9600);
    pinMode(C1P, OUTPUT);
    pinMode(C1N, OUTPUT);
    pinMode(C2P, OUTPUT);
    pinMode(C2N, OUTPUT);
    digitalWrite(C1P, LOW);
    digitalWrite(C1N, LOW);
    digitalWrite(C2P, LOW);
    digitalWrite(C2N, LOW);
    delay(1000);
}
// anticlockwise is towards the motor
void anticlockWise (int notch_count) {
    int count_notches;
    for (count_notches = 0; count_notches < notch_count;
        count_notches++) {
        switch (stepper_state) {
            case idle : digitalWrite(C1P,HIGH);
                        stepper_state = state_0;
                        delay(torque);
                        digitalWrite(C1P,LOW);
                        break;
            case state_0 : digitalWrite(C2P,HIGH);
                        stepper_state = state_3;
                        delay(torque);
                        digitalWrite(C2P,LOW);
                        break;
            case state_1 : digitalWrite(C1N,HIGH);
                        stepper_state = state_0;
                        delay(torque);
                        digitalWrite(C1N,LOW);
                        break;
            case state_2 : digitalWrite(C2N,HIGH);

```

```

        stepper_state = state_1;
        delay(torque);
        digitalWrite(C2N,LOW);
        break;
    case state_3 : digitalWrite(C1P,HIGH);
        stepper_state = state_2;
        delay(torque);
        digitalWrite(C1P,LOW);
        break;
    }
    delayMicroseconds(gap);
}
}

// the loop routine runs over and over again forever:
void loop() {
    Serial.println("Going Clock wise away from motor");
    clockWise(6000);
    delay(1000);
    Serial.println("Going Anti Clock wise towards motor");
    anticlockWise(6000);
    delay(1000);
}

```

SOLAR REFOCUSSING IN CENTRAL RECEIVER TOWER POWER PLANTS

The solar trackers above are used to identify sun vector or direction of the sun viewed from the power station site. The coordinates or direction of the solar absorber from each heliostat will be determined and known. There will be East, West, North and South of the power station solar trackers. These solar trackers communicate among themselves and the East solar tracking device calculates the average sun vector and broadcasts to all heliostat mirrors this average solar vector. The average of this solar vector and solar absorber vector from each heliostat which will be calculated by each heliostat's Arduino will be the normal to the mirror. If we add 90° and subtract 90° to this normal vector, we will find the heliostat alignment angle.

Conclusions

Two solar tracking mechanisms were identified (1) the gear wheels driven by stepper motors that are controlled by 'c' programme in Arduino and (2) the hydraulic mechanisms. These two solar tracking mechanisms could be employed to ascertain the direction of the solar body from the power station or sun vector for each heliostat mirror in Power Tower power stations. The hydraulic sun tracker and the Light Dependent Resistor or photodiode trackers respond to unequal solar flux while the chronological solar tracker responds to time or time intervals from set point.

The thesis now proceeds to design a solar absorber also known as a receiver for the 500 MW Central Receiver Tower power plant.

3.6 DESIGN OF SOLAR THERMAL ABSORBERS FOR POWER TOWER POWER PLANTS.

INTRODUCTION

The purpose of this section is to demonstrate the design a solar absorber for a Central Receiver Tower power stations of rating 500 MW. The section posits that a solar absorber also called a receiver is an important, vital, imperative and key component or gadget installed on the Central tower's top of a Central Receiver Tower (CRT) power plant. The paper also reviews literature of Solar absorbers and highlight challenges in the design of receivers. The problem is the difficulties met during the design of durable solar absorbers given thermal, optical and mechanical stresses they are subjected to. The section highlights that excessive localized thermal flux maxima on certain parts of the absorber may lead to receiver damage or reduced life expectancy. This highlights the need for evenly distributing sunlight energy on all the external surfaces of the receiver from the heliostats. The method of designing solar absorbers involves materials' thermal and optical behavior as well as mechanical strength analysis. A solar absorber to output 500 MW given 565 °C average operating temperatures and specific heat capacity of the thermal energy Transfer fluid is used to calculate the dimensions of the thermal absorber. An absorber of height 10m and radius 5.3m was found to be appropriate for a 500 MW power plant.

The section tries to highlight materials covered in current literature consulted so far and even try to recommend new materials such as diamond or graphite with the highest heat conductivity of all naturally occurring substances. Diamond possess a heat conductivity that is 11 times higher than that possessed by aluminum metal and 30 times greater than that possessed by iron. Factually, it can be considered the best thermal conductor among all known substances found in nature (Rosa, 2009), but has prohibitive costs. A material analysis was done with the hope that better materials than those recommended by literature are identified.

Materials e.g. metals will be compared with regard to heat conductivity, reflectivity, mechanical strength and ability not to react with the intended thermal energy transfer fluid such as molten salt (a mixture of potassium nitrate and sodium nitrate in

appropriate proportions). This paper has tried to explore considerations and issues involved in the design of a solar absorber for e.g. a 500 MW Central receiver tower power plant for Kadoma District in Zimbabwe. A typical solar absorber is normally 4 to 6m long or even longer. The significance of the paper is that it will increase perspectives and approaches in solar absorber design and provide a design methodology template for solar absorbers.

The section concludes by recommending accelerated research in the design of solar absorbers for Central Receiver Tower power plants. Advances in optical, thermal, mechanical and therefore durability properties are important for overall plant efficiency. Further research in material sciences, mechanical strengths and densities of various possible materials for use in the design of solar absorbers is also recommended.

Keywords

Solar Absorber(SA)

Heat Transfer Fluid(HTF)

Absorptivity

Reflectivity

Conductivity

Receiver

1.0 MAIN NARRATIVE

Release of greenhouse gases, ozone layer depletion and subsequent together with subsequent need for ‘change of climate’ retardation have made green generation imperative like Concentrated Solar Heat Power Plants E.g. Solar Tower Power plants. There is a forcing need to lower down fossil fuel generation in favor of clean electric energy generation. All the Solar Tower Power Plants require receivers which are also called solar absorbers.

A solar absorber is alternatively known as a receiver or heat-collecting element. The receiver is an indispensable, essential and critical component in Power Tower Power Plants also known as Central Receiver Tower Power Plants. The duty of the receiver is that it is a point of solar concentration and it captures most solar flux from the heliostat mirrors. It also heats up the Thermal Energy Storage Fluid inside it to average temperatures of about 565 °C or even more. The receiver transforms solar flux into heat. Therefore, its outside high heat absorptivity and low reflectivity since all the heat must be absorbed by the receiver for purposes of heating the Thermal Energy Storage Fluid (TES)

According to Charpentier (2019), an ideal solar absorber would avail an emissivity close to 0 and an absorptivity close to 1. It is made from high temperature materials. According to Ferrari et al (2021), material choice of the solar absorber affects factors such as plant capacity, temperature range and thermal transfer attributes. This means the outside of the solar absorber must have an antireflective material and the metal must be rough and painted black to ensure this desirable attribute since rough dark or black bodies are good absorbers of heat. According to Blanco and Santigosa (2017), the durability, thermal and optical properties of a solar absorber are critical in its design for improved operational efficiency and lower costs. Yan Luo et. al (2015) talks of receivers of 10m height and a diameter of 7m and 8m.

The desirable attributes of an ideal solar absorber should include good heat absorptive properties and bad reflectivity on the outside, a good emitter of heat inside, it must be large enough and positioned to capture as much solar heat rays as

possible from the heliostat assembly. The volumetric expansivity of the heat storage fluid inside ‘receiver’ must be such that the forces generated due to such expansion must be within the mechanical withstand strength value of the walls of the thermal absorber unit. Thermal levels as high as 1000°C could be attained in the central receiver or solar absorber. The surface temperatures of a solar absorber ranges between 400°C to 1000°C although some literature gives 565°C as the normal functioning thermal levels of the HTF in the storage tanks. It means temperatures in the solar absorbers must be slightly higher and the materials used to manufacture such must have a melting point higher than 1000 °C.

There is need for solar flux from the heliostats to be evenly distributed around the outer body of the receiver to prevent localized hotspots maxima that may damage the solar absorber. This is achieved by having different and distributed aim points on the receiver for the different sets of heliostats. The paper says that the inside Heat transfer fluid temperature may be used for feedback control.

MATERIALS AND METHODS

The improvement and advances in solar absorbers has capacity and ability to improve the overall plant’s efficiency of a CSP power plant (Dao and Cho (2018)). The absorbers are inclusive of metallic plasmonics, semiconductors, carbon and natural materials. According to Chandrashekara and Yadav (2017) there are also absorbers made of diamond-like carbon thin films on aluminum substrates. Among absorber materials, carbon-based materials have low cost, excellent light-to-heat conversion and reusability properties [9]. Cermet solar absorbers offer the advantages of both ceramics and metals. They have high temperature stability, attractive thermo-physical and good thermal conductivity. Urania-nickel cermets with 20 and 30 % weight nickel are also available.

Rough, selective, inhomogeneous and low cost aluminum-graphite (C/Al₂O₃/Al) radiation surface which absorb solar and provide at the correct state of advancement, solar absorptance with thermal emittance $\epsilon=0.22$ and solar absorptance $\alpha=0.90$ (Konttinen and Lund (2018)) so as to achieve lower emittance, silicon carbide

grinding surface and corresponding grinding pattern require to be improved. Joly et al(2014) posits that no naturally occurring material has perfect intrinsic selective properties. An optimal coating that is selective on the solar absorber is needed so as to enable the outer receiver's surface to act as a black body. Joly et al (2014) says that a surface that is selective has least potential spectral reflectivity within the range of spectrum and the highest practical on the infrared scale. Joly et.al. (2014) emphasizes that selective coatings for receivers are either made or manufactured by vacuum deposition or electrodeposition of black chrome process like evaporation that is reactive or magnetic sputtering. $\text{Al}_2\text{O}_3\text{Ni}$ absorbs 97 % of the incoming solar energy. A coating that is selective and is also black can be manufactured by sol-gel dip-coating.

An anti-reflective coating could improve α to > 0.90 (Konttinen and Lund (2018)). The transformation of sunlight flux or insolation into heat energy need spectrally selective solar absorbers Konttinen and Lund (2018). Solar absorbers which are state of the art possess longer durability and good optical properties i.e. heat absorptance which is near to 1 and thermal emittance ε near zero. (P. Konttinen and P.D. Lund (2018)). These absorbers have a high cost and are manufactured by sputtering Konttinen and Lund (2018). The major idea is to make the aluminum pad rough and then add graphite layer mechanically onto it at the same time. Solar absorbers normally have a life expectance of 25 years Konttinen and Lund (2018). Graphite powder mixed with black paint is normally used to paint solar absorbers Sani et al (2018).

A solar absorber should efficiently, effectively and decisively capture, absorb and harvest sunlight flux or insolation whilst competently transforming it to thermal energy by concentrating solar energy so as to heat the Thermal Energy Transfer Fluid (TETF) inside the receiver. Selective solar receivers enable this by absorbing high quantities of sunlight wavelength availed at the surface of the earth while suppressing components of infra-red from re-radiation resulting from the heating of the receiver Bermel et al (2002). It involves absorbing short wavelengths upto a critical cutoff wavelength, and reflecting everything else and hence the selectivity of the solar absorber. The selective solar absorbers include semiconductor metal tandems, intrinsic absorbers, multilayer tandems, ceramic-metal composites

(alternatively known as cermet), photonic crystals and textured absorbers Bermel et al (2012). As far as wavelength, angle and polarization is concerned, cermet have the highest performance with Photonic crystals having potential for improvement in future Bermel et al (2012). Cermet coatings based Receivers possesses low emittance in components of the sunlight spectrum within the infrared IR portion and high absorptance of the solar spectrum. Cermet are ceramic metal composite materials.

Cr_2O_3 , Al_2O_3 , AlN , SiO_2 and ZrO_2 are cermet based spectrally selective receivers which possesses low thermal emittance and high solar absorptance. The cermet acts as absorption layers and these have high conversion efficiency and high thermal stability in the conversion from solar radiation to heat. The performance of cermet is the highest among the simple structures and photonic crystals were found to have the greatest potential for improvement in future because of selectivity with respect to polarization wavelength angle (Cao et al.,2014)

Tetrahedral diamond structured solar cell material and its derived structure (i.e. chalcopyrite and zinc blende) are the highest in terms of success in the family of materials with a power conversion efficiency surpassing 20% Yang et al (2018). Recently lead halide perovskites have attracted research efforts. Key challenges that lead halide perovskites faces are stability and toxicity issues Xu et al (2018).

Spectrally selective receivers efficiently trap and pass solar energy heat to the heat transfer fluid inside them Cao, McEnaney, Chen and Ren (2014). As mentioned before, cermet coated based solar absorbers have high absorptance among the solar radiation spectrum and a minimal emittance in the infrared spectral region Cao et al (2014). Cermet based solar receivers are optimized to attain high performance through techniques such as solution-based techniques, pulsed laser deposition, sputtering and electrodeposition techniques Cao et al (2014).

Silica-carbon hybrid materials can also be used as selective solar absorber material Mastai et al (2002).

2.0. Properties of various Materials

The values below were obtained from a report by Metal Supermarkets (2020) and Research Institute

<u>POSSIBLE HEAT TRANSFER FLUID MATERIAL</u>	<u>MELTING POINT</u> (° C)	<u>BOILING POINT</u>	<u>DENSITY</u> (g/cm ³)	<u>THERMAL CONDUCTIVITY(W/Mk)</u>	<u>COMMENTS</u>
Silver	961	2 162	10.49	430	
Ruthenium	2 334 °C	4 150 °C		1.1 W cm ⁻¹ deg ⁻¹	
Copper	1 084	2 562	8.96	400	
Gold	1 063	2 700	19.32	320	
Aluminum	660	2 470	2.7	235	
Calcium	842	1 484	1.56	200	
Beryllium	1 287	2 469		190	
Magnesium	650	1 091	1.738	160	
Silicon	1 410	2 355	2.32	150	
Carbon	3 550	4 815		140	
Sodium	97.79	882.8	2.26	140	
Stainless Steel	1 375- 1530	Non	7, 500 kg/m ³	15 W/K/m	
Carbon Steel	1 425- 1 540			45 W/K/m	
Lithium	180.5°C	1342 °C	0.534g/c m ³ as a solid	80 W/Mk	Lightest element of all solids
Liquid Potassium	63.5	758.8	0.862 g/cm ³	102.5 W(m-K	
Potassium Nitrate	334 °C	400 °C	2.11 grams per cm ³	0.62 W/K	
Diamond	700 °C	4 830 °C	3.5 g/cm ³	2 000 W/m-K	Best material to be used as a

					solar absorber
Graphite	3 400 °C	4 200 °C	2.26 g/cm ³	1 950 W/m-K	
Zinc	419.5 °C	907 °C	7.13 g/cm ³	112.2 W/m-K	
Asbestos	1 482 °C		0.36 g/cm ³	0.182 W/m-K	
Ceramic	2 000 °C		6 g/cm ³	1.10 W/m-K	
Concrete	900 °C		2.4 g/cm ³	2.25 W/m-K	
Sand	1 550 °C	2 230 °C	1 680 kg/m ³	2.05 W/m-K	
Silicon	1 420 °C	2 600 °C	2.329 g/cm ³	2.3 W/m-K	
Germanium	938 °C	2 833 °C	5.323 g/cm ³	1.45 W	
Quartz sand	1 650 °C	2 230 °C	2.65 g/cm ³	7.7 W/m-K	
Cement	1 550		1.44 g/cm ³	0.7 W/m-K	
Silica	1 200 °C		2.65 g/cm ³	1.31 W/m-K	
Granite	1 260 °C		2.65 g/cm ³	7 W/m-K	
Selenium	220 °C	688 °C	4.28 g/cm ³	2.04 W/m-K	
Uranium	1 132 °C	3 818 °C	19 g/cm ³	27 W/m-K	
Plutonium	639.4 °C	3 228 °C	19.84 g/cm ³	0.03 W/cm-K	
Chlorine	-101.5 °C	-34.04 °C	3.214 g/litre	0.00009 W/cm-K	
Fluorine	-219.8 °C	-188.1 °C	1.696 g/litre	0.0279 W/m-K	
Fibreglass	1 135 °C		2.44 g/cm ³	0.05 W/K m	
Porcelain	1 927 °C		2.4 g/cm ³	1.5 W/m K	
Polyvinyl chloride(PVC)	100-260 °C		40 kg/m ³	0.136 W/m K	

Expanded polystyrene	100 °C		1.05 g/cm ³	0.037 W/m K	
polyurethane	44.1 OC	232 OC	30 kg/m ³	0.025 W/m K	
Alcohol	-114 OC	78.4 OC		0.481 W/m K	
Iron	1 538 OC	2 862 OC	7.87 g/cm ³	80 W/m K	
Ruthenium					

TABLE 8

Materials with melting points below 1100^o C such cannot be considered for manufacturing of solar absorbers. The possible materials also need to be good thermal conductors.

Materials that can be considered for manufacturing solar absorbers above are graphite (melting point 3 400 °C). Literature talks of silica-carbon, cermet, chalcopyrite, zinc blende, chromium oxide, aluminum oxide, silicon dioxide, ZrO₂, ceramic and photon crystals,

An almost ideal material for solar absorption is manufacturing solar absorbers from a two dimensional metallic (e.g. ruthenium) dielectric photonic crystal. It has the following benefits Chandler (2014).

- (1) The solar insolation or irradiance can be absorbed from a wide range of angles
- (2) The material can withstand extremely higher temperatures
- (3) cheap manufacturing process at a large scale is possible
- (4) It is well suited to existing manufacturing technology Chandler (2014).

A collection of Nano-cavities is used to manufacture the material. It is possible to synchronize the absorption by altering the dimensions of the Nano cavities. Use is made of a relatively costly metal called ruthenium to manufacture the solar absorbers

Kant et al (2022) posits that fractal multiscale texturing of receiver surfaces greatly increases solar absorption for CSP power plants. Surface profiling measurements determine fractal parameters. Kant et al (2022) says that fractal surface texturing

reduces reflectance by over one order of magnitude availing an absorptance of more than 0.985 for CuMnO.

A typical solar absorber tube is 4 to 6 m (Santigosa., 2017)

In order to enhance thermal and optical properties and durability of solar thermal electricity generation plants, solar absorbers are among the very important components.

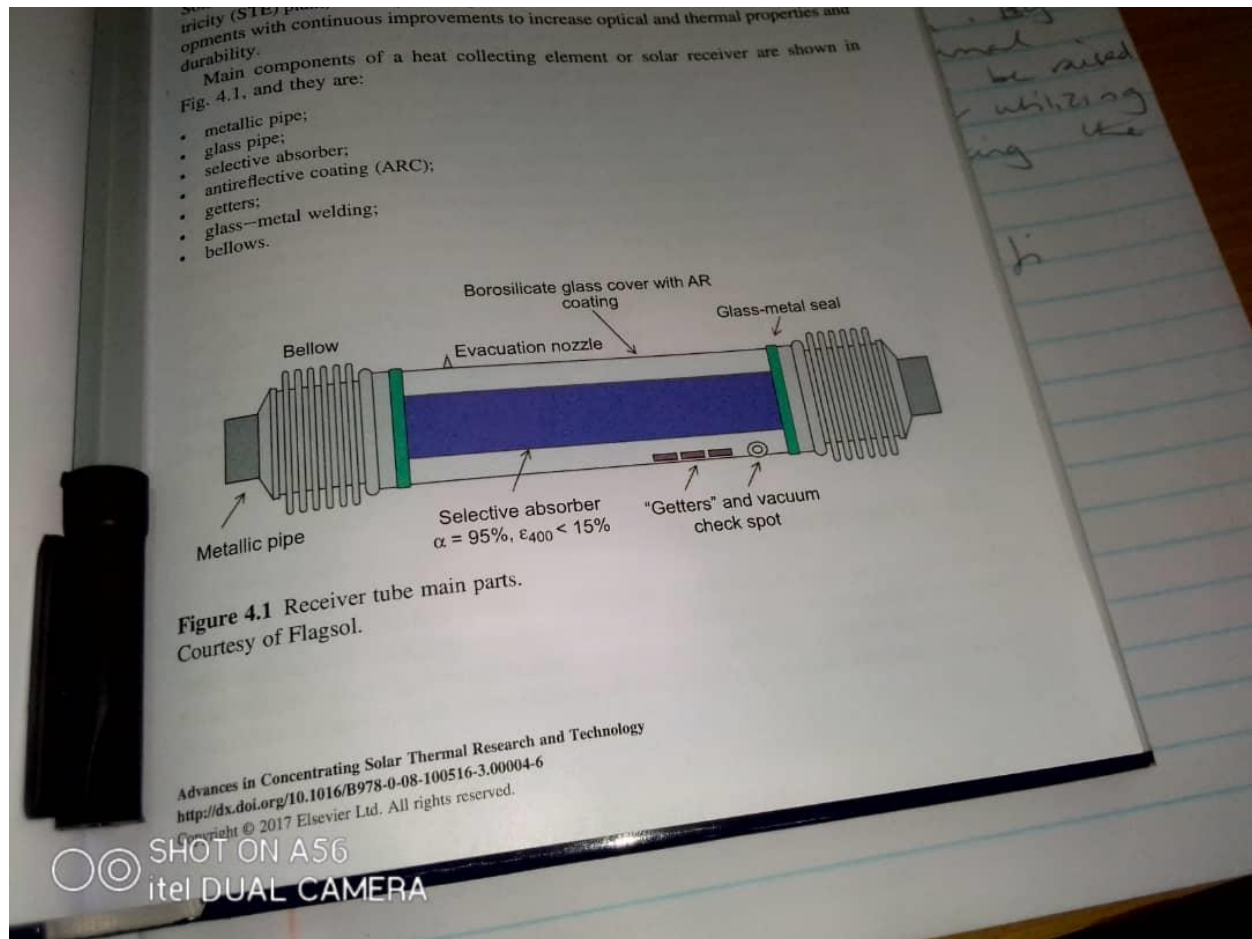


Figure 56

The major components of a solar absorber or solar receiver according to Blanco and Santigosa (2017) are: -

1. Metallic tube
2. Glass tube

3. Selective absorber
4. Anti-reflective coating(ARC)
5. Getters
6. Welding of metal-glass
7. Bellows.

Metallic expansion bellows are employed to facilitate and enable connection of the glass cover to steel pipes in order to trade off for differential linear heat expansivity possessed by steel compared to glass when the receiver or heat absorber is functioning at normal temperatures. Flexible bellows and glass is connected by glass to metal welding which protects it from concentrated heat radiation in order to prevent heat and stresses that are mechanical which can possibly have impact on welding durability and performance. The thermal energy transfer fluid will be pushed whilst being made to flow via the metallic tube in order to absorb heat collected using the selective receiver, therefore a vacuum is created in the annulus to diminish thermal heat losses.

The performance of the ‘Solar Heat Electricity Energy Plants(SHEEP)’ is greatly linked to the thermal and optical attributes quality of the receiver assemblage together with the operating thermal levels. Mostly employed oil-based heat transfer fluid (HTF) are however limited to operating temperatures of around 400 °C and as a result restrict the overall station efficiency. Use of high temperature Thermal Energy Transfer Fluid (TETF) like molten potassium nitrate and or sodium nitrate is a major innovation to circumvent this limitation. Direct steam generation also facilitates operation temperatures upto 550 °C.

Extended pipes give a highly valuable surface, low expensive welding inter-pipes, bigger receivers need fewer controls and servomotors.

Major deterioration problem identified in solar absorber tubes, working in the sunlight heat power stations (SHPS) that operate commercially is loss of vacuum in the inner annulus created by the diffusion of hydrogen coming from oil-based heat transfer fluid via tube walls. In order to diminish the partial pressure imposed by hydrogen in the vacuum annulus, getters have been employed extensively, except that the 25 years anticipated longevity will not be attained. Transition from oil-based heat transfer fluid schemes to direct steam generation or molten salts will scale down

vacuum deterioration challenges and would assist to diminish solar absorber tube expenses.

3.0 Parts of a Solar Absorber

3.1. GLASS COVER

Heat collectors or receivers exploit glass covers to diminish convective losses of heat together with protecting absorbers that are selective from outdoor and atmospheric exposure. Pipe of glass is concentric to the metal receiver tube. It also requires a higher sunlight transmittance and a reduced heat expansivity coefficient to make available excellent 'heat resistance of shock', near the heat coefficient of the receiver pipe made from metal at operation thermal levels so as to belittle the mismatch existing between both linear expansivity coefficients.

Vacuum is established inside the annulus between metallic pipes and glass in order to diminish heat losses by convection-conduction and prevent heat oxidation of the selective receiver deposited on the tube made of metal. Metal-glass welding is employed to seal the annulus and the bellow made from metal is employed to trade off for this mismatch of expansion coefficients between metal pipes and glass.

3.2 GLASS COMPOSITION

The material made of glass that is employed as the cover of the glass in heat collector elements (HCE) has to be borosilicate glass. Borosilicate has an extremely low coefficient of thermal expansion and as a result is highly resistant to thermal shock.

The existence of great or huge quantities of boric oxide ($B_2O_3 > 8\%$), silica (SiO_2), glass network formers characterize the glass.

So as to amplify the coefficient of expansion to a level near that of stainless steel, there is need for the addition of alumina and alkaline earths.

Borosilicate glass possess a solar transmittance ranging from 0.90 to 0.83, excellent outdoor longevity and good thermal shock resistance. Borosilicate glasses mainly employed in sunlight absorbers are as follows: -

- Borosilicate 5.1 It possesses a solar transmittance of around 0.92 and excellent mechanical and chemical attributes to be used in this application. It has a linear expansion coefficient of $5.1 \times 10^{-6} /K$.
- Borosilicate 3.3 It lacks alumina and alkaline earths in its architecture. It possesses a solar transmittance of around 0.92, excellent chemical properties and a small thermal expansion coefficient that avails the biggest thermal shock resistance.

3.3 ANTI-REFLECTIVE COATINGS(AR)

Antireflective coatings possess about 150 nm thickness and a value of 1.22 refractive index. The glass jacket of a solar absorber is coated on both sides by a film to scale down the losses of reflection within the glass and in the process amplifying the optical efficiency of the solar absorber tube.

Silicon dioxide is frequently employed as antireflective coating material. Porosity in coatings results in low refractive index.

3.4 STEEL TUBE

Thermal energy transfer fluid is pushed via the receiver metallic tubes along the lines of the receiver so as to have its temperature raised by sunlight flux that is concentrated. The metallic tube requires to fulfil many requirements: -

- The heat accumulated by the selective receiver deposited on their outer surface is facilitated by excellent thermal conductivity.
- Excellent corrosive resistance in respect of thermal energy transfer fluid employed in the system.
- An example of a receiver tube has a length of 4.06 m at room temperature.

In order to understand thermal dynamics within a solar absorber we need to understand the 3 methods of thermal energy transfer. These methods include radiation, convection and conduction. The transference of heat energy throughout the body which result from the movement of molecules which is stochastic is called conduction (J. Andrews and N. Jelley (2013). The molecules' average energy is proportional to the thermal level of the body i.e. heat solar absorber in our case.

Fourier's law of heat conduction is as follows

$$Q = K_a (T_1 - T_2) / d$$

Where k = thermal conductivity

d = length of bar (from point of entry of heat to the solar absorber to the point of exit of heat to the HTF)

Convection is defined as the process whereby the bulk motion of a fluid results in the transportation of heat (J. Andrews and N. Jelley (2013)).

If we assume a HTF of density ρ and temperature T moving with a velocity u . The mass flow per

unit area per second is ρu and the thermal energy per unit mass is CT . The rate of flow of heat per unit area by convection is the product of ρu and CT i.e.

$$Q/A = (\rho U) (CT) = \rho U CT$$

The transmission of energy through propagation of electromagnetic through space or media which is transparent is called radiation. Wavelength relate to its properties.

The fundamental laws of physics guide how bodies' surfaces emit energy through electromagnetic radiation.

The solar absorber in a Central Receiver Tower power plant is normally referred to as a boiler in other literature or just as central receiver. The nomenclature varies from one author to another

The original unit of measuring thermal energy was the Calorie which is the energy required to alter the thermal level of one gram of liquid water by one degree Celsius.

Recently the unit of measuring thermal energy was changed to the joule where 1 calorie=4.2 joule J. Andrews and N. Jelley (2013).

4.0 PERFORMANCE ANALYSIS R.K. Singal(2008) The speed of useful thermal energy produced from a receiver or absorber is given by the following equation: -

$$Q_1 = E - \sum E_1 - \sum Q_l \quad (\text{W}) \text{ Equation}$$

Where

E=output of heliostat field in Watts

$\sum E_1$ =Electrical losses in Watts (Reflection radiation losses from the solar absorber's surface).

$\sum Q_l$ = Heat losses in Watts caused by radiation, convection and conduction in the solar absorber's walls

The rate of beneficial thermal energy(heat) output is also equal to

$$Q_1 = Aa(I_a - F_g U_o(T_{in} - T_a)) \quad \text{in Watts}$$

$$= in(h_o - h_1) \quad \text{in Watts}$$

The absorber solar radiation flux

$$I_a = \frac{(E - \sum E_l)}{A_a}$$

$$= I_b C_p \tau \alpha \quad \text{Watts/ m}^2$$

Where I_b =Beam radiation intensity on heliostat surface Watts per m^2

C=concentration ratio of heliostat receiver system

ρ =Reflectivity of heliostat

γ = Intercept factor

τ = Transparent cover's Transmissivity

α = Absorptivity of receiver surface

The efficiency $\eta = Q_c/E$

Where E= Beneficial solar radiation flux of the heliostat in Watts

4.2 THERMODYNAMICS

The units of energy include the electron-volt, foot pound, calorie, the British thermal unit(BTU) and the joule Chakrabarti (2011). We need these units to measure heat energy absorbed by the receiver or absorber and the energy sent to the heat energy storage tanks from the absorber.

Enthalpy: is the heat content of an object or substance under consideration. In the case of a solar absorber the total heat in the HTF is its enthalpy. We are also concerned about the enthalpy in the energy storage tanks and its capacity to drive a heat engine or power block using superheated steam.

$h = \text{Internal energy} + (\text{Pressure} \times \text{Volume})$

where h =Enthalpy

Entropy: A system's energy is considered to be the sum of useless and useful energy. The useless or scrape energy is called entropy. The prevalence of entropy over the sum total energy of the body or system is proportional to the absolute temperature of the system in question and in our case the solar absorber.

Energy output from the absorber=Energy input to the absorber - (minus) losses to the surroundings

4.3 Thermodynamics' First Law

Thermodynamics' First Law posits that energy can neither be created nor destroyed Chakrabarti (2011).

In a closed system, executing a cycle (in which the end state is the same as the initial state), the net energy delivered to the surroundings is proportional to the net heat taken from the surroundings Boyle (2012). In other words, heat and work are mutually convertible and they should be in the same units.

The First Law of Thermodynamics is expressed as follows: -

$$E_2 - E_1 = Q - W$$

Where Q=Heat added to the solar absorber

W=Work done or enthalpy to energy storage tanks

$E_2 - E_1$ =change in contained or stored heat energy found at the boundary states 2 and 1 of the solar absorber system.

$$\psi dw = \psi dq$$

$$\psi(dq - dw) = 0$$

Where

Where

ψ_{dw} = Network delivered to the surrounds during the cyclic process

ψ_{dq} = Net heat taken from the surrounding during the cyclic process

SECOND LAW OF THERMODYNAMICS

All types of energy, work also included, can be converted to heat, but generally the converse is not true.

No actual engine operating in cycles can convert all the thermal energy(heat) supplied to it into work. This means that some of the energy is lost to the atmosphere or rather surroundings.

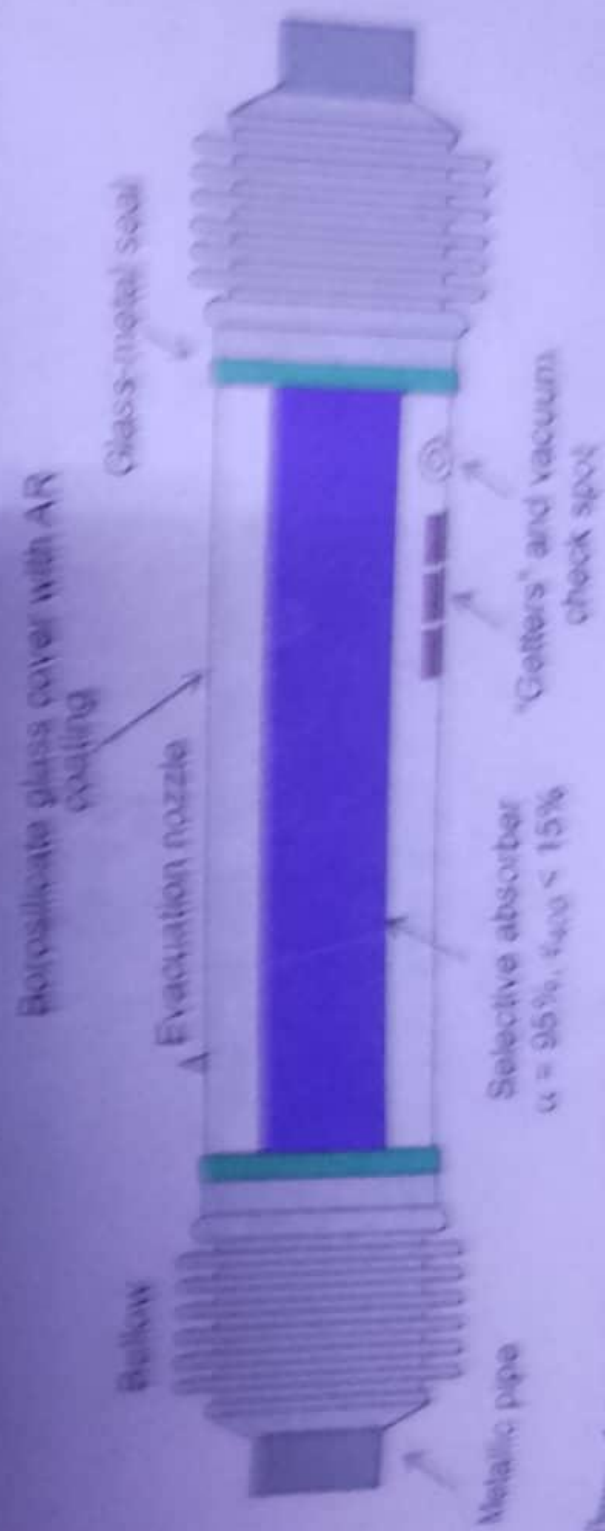


Figure 4.1 Receiver tube main parts
 Courtesy of Flagsol

Figure 57

Three considerations are important in sizing a solar absorber namely: -

- (1) Absorber average operating temperatures
- (2) Power output requirements of the power station (500 MW)
- (3) Specific heat capacity of the thermal energy transfer fluid.

The thermal level rise of the HTF depends on solar intensity at the site of the power station and the tracking efficiency. Assuming a plant overall efficiency of 20%,

$$20\% = 500 \text{ MW}$$

$$100\% = 2\,500 \text{ MW}$$

$$2\,500 \text{ MW} = mc\Theta$$

Where m = mass of the thermal energy transfer fluid from the receiver per second

C = specific heat capacity of the HTF

Θ = temperature rise per second in the HTF

$m = V\rho$ where V = internal volume of absorber, ρ = density of HTF

$$2\,500 \text{ MW} = V\rho c\Theta$$

Reflectivity = 94% therefore losses = 6%

Attenuation = 92 % therefore attenuation losses = 8 %

Blocking & shading efficiency = 94%, therefore blocking & shading losses = 6%

Total losses before absorber = 6 + 8 + 6 = 20%

$$100\% = 2\,500$$

80% = 2 000 MW reaching the absorber = 2 000 000 Kw

$$Mc\Theta = 2\,000\,000$$

Specific heat capacity of potassium nitrate = $1.118 \text{ J/gK} = 1118 \text{ J/Kg K}$

Density of potassium nitrate = $2.11 \text{ g/cm}^3 = 2110 \text{ kg/m}^3$

$Mc\Theta = 2\,000\,000$

$M = 1\,825$

$10\pi(r^2) = 865$

For single tower, Assuming a height of 10m of solar absorber

$\pi(r^2) = 86.5$

$r^2 = 28$

$r = 5.3 \text{ m}$

For double tower, assuming a 10m high solar absorber

$2\pi r^2 = 86.5 \text{ m}$

$r^2 = 13.7$

$r = 3.7 \text{ m}$

For a 5 tower, assuming a 10m high solar absorber

$r^2 = 5.5$

$r = 2.4 \text{ m}$

Therefore, the dimensions of the absorber are 10m high with a radius of 5.3m for single tower

3.7m for double tower and 2.4m for 5 towers

$$V = \frac{(2000 \text{ MW})}{\rho c \theta} = 200\,000 \text{ kW}$$

According to Heliyon (2021), reducing the solar absorber dimensions assists in reducing the spillage loss but there will be an increase in thermal stress. Inserted longitudinal triangular fins in the absorber increases the transfer of heat as well as making the absorber tube stronger.

Key Assumptions Made

- (1) The solar absorber is always functioning. In practice the receiver may develop solar intensity fatigue and become faulty e.g, leaks needing repair
- (2) All the heat from the receiver reaches the heat exchanger. In practice some heat may be lost to the atmosphere.

6.0 Areas for Future Research

. Delete this paragraph. Not possible

7.0 Conclusions

A solar absorber is a vital part of a Central Receiver Tower Power station. A typical solar absorber for a 500 MW power plant has a height of about 10m and an internal radius of about 5.3m. Assuming a thickness of 1cm, outer radius for the metallic pipe= 5.31m. For double tower the radius of each of the two absorbers is 3.7m and for 5 tower 2.4m. The optical, thermal and mechanical properties of materials used to manufacture a solar absorber are very vital considerations in designing an absorber or receiver. A solar receiver is made from high temperature materials. An ideal solar absorber would avail an emissivity close to 0 and an absorptivity close to 1. More research needs to be done in the improvement of solar absorber design to realize more plant efficiencies.

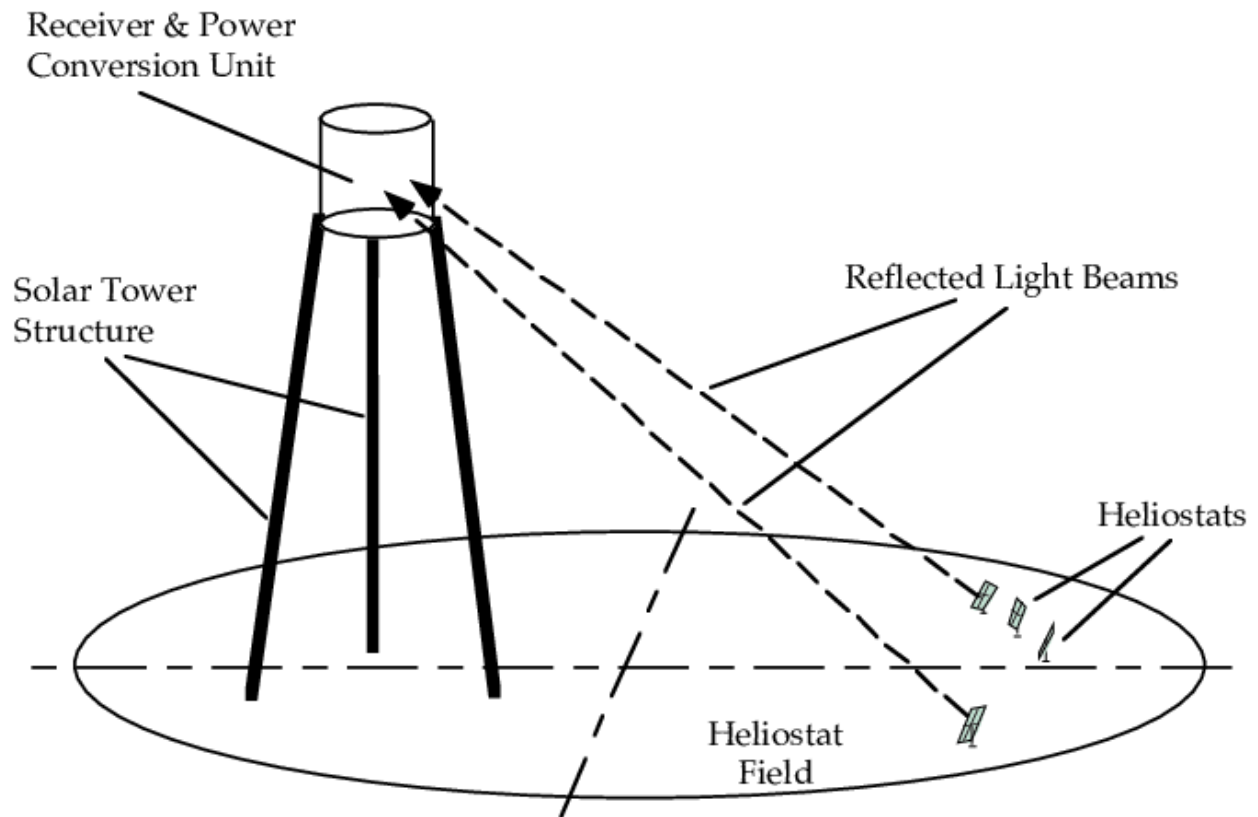


Figure 58

The thesis now proceeds to design a heat exchanger for the 500 MW CCTPP.

3.7 DESIGN, DIMENSIONING AND SIZING OF A HEAT EXCHANGER FOR A 500 MW POWER TOWER POWER PLANT

INTRODUCTION

This section investigates materials from which heat exchangers for a Central Receiver Tower power plant can be made from. Various kinds of heat exchangers are highlighted together with the construction structure of heat exchangers are highlighted.

In this project heat exchangers are also called ‘thermal energy exchangers (TEE)’ or simply ‘thermal exchangers’.

Parallel flow and Counter-flow heat exchangers are compared and the conclusion is reached that counter-flow heat exchangers are far more superior than parallel flow heat exchangers for Concentrated Solar Thermal Power Plants of the Power Tower kind in terms of thermal performance and thermal transfer capabilities. The heat transferred per second is proportional to the temperature differences between the 2 fluids i.e. the Thermal Energy Transfer Fluid and the working fluid. The higher the temperature difference, the higher the rate of heat transfer per second.

Possible materials for manufacturing heat exchangers are compared in terms of mechanical strength, thermal conductivity, state at operating temperatures between 565 °C and 1000 °C and corrosive resistance capabilities. Diamond and graphite are single out as the best materials for manufacturing heat exchangers, but cost considerations may act against diamond use. Diamond is a very expensive material. These are followed by copper in terms of preferability. Silver which was supposed to be the second best was disqualified because of the smoker’s experience it presents to those nearby.

Diamond is an inert element that is corrosive resistant which makes it an excellent candidate material for manufacturing of heat exchangers for CSPs of the CRT type, had it not been for its prohibitively high price. If cost is not an issue diamond is the ideal material amongst all naturally occurring materials.

The section concludes by positing that so as to enhance the heat exchanger pipes' surface area within boilers (Heat Transfer Fluid to Working Fluid) or condensers (steam to cooling water) have to be many, numerous and plenty with small diameters and made from good heat conductors.

The section concludes by actually sizing in terms of dimensions the heat exchanger for a 500 MW Central Receiver Tower power plant type.

MAIN NARRATIVE

The rising demand for green generation has made it imperative to design and build Sunlight Heat Power Stations (SHPS) which need heat exchangers. The problem is to come up with manufacturing materials given high thermal stress that heat exchangers are subjected to. The materials must have high heat conductivity e.g. diamond (if cost is not an issue) or graphite. Material analysis is therefore necessary in order to design superior heat exchangers.

The volumetric dimensioning of heat exchangers depends on the designed electrical output of the power station concerned. This informs the quantity of enthalpy that should be transferred to the working fluid or cooling water in the boiler or condenser.

A heat exchanger is a gadget or equipment that allows, facilitates or encourages heat or thermal exchange (to and fro) between two different fluids or solids through it and separated by itself (Edrels and Petrov., 2020). It facilitates the movement of heat from a thermal source normally a thermal energy transfer fluid to a heat sink which is the working fluid being a conduit of heat flow. The 2 fluids are normally separated by a wall (the heat exchanger surface) to prevent them from mixing. Furthermore, for heat exchange to occur, the two fluids must be at different temperatures. In Central receiver Tower power plant, a heat exchanger allows heat to be transferred from Heat transfer fluid e.g. molten salt to the working fluid e.g. water to generate super-heated steam. The heat exchanger has a great influence on the thermal energy transfer performance and therefore overall efficiency of the Central Receiver Tower power plant. When water changes phase to steam there is a volume or expansion gain of the order of 1 600 times more resulting is massive pressure which drives the prime mover or turbine that rotates the generator in turn thereby generating electrical energy.

Heat exchangers are also employed in cooling towers and condensers in CSP power plants. They affect the overall plant efficiency and plant sizing. Surface enhancers such as fins, turbulators and other microstructures can enhance their thermal transfer efficiencies. A cooling tower is a type or form of a thermal energy exchanger.

A thermal energy exchanger is a necessary, essential as well as a critical part of a CSP power station of the Central Receiver Tower Type. It facilitates transfer of heat from the Thermal Energy Transfer Fluid (TETF) (normally molten salt) to the working fluid (normally water) that generates steam needed to drive a heat engine or power block. This means it must be an excellent heat conductor. Best conductor of thermal energy identified by this project in literature is diamond which is a very hard material. Diamond has a heatl conductivity 11 times larger than that of aluminum and 30 times that of iron. Actually it is the best heat conductor of all naturally occurring substances in nature (A. Vieira da Rosa., 2009: p170). This implies that it is logical to investigate the possibility of using diamond as a possible heat exchanger material.

TRADITIONAL MATERIALS FOR HEAT EXCHANGERS (Sterling Thermal Technology Report.,2022)

- Stainless steel
- Copper
- Duplex
- Super duplex
- Monel
- Cupronickel 70/30 and 90/10
- Carbon steel
- Admiralty brass
- Aluminum brass

MATERIALS FOR CORROSIVE RESISTANT HEAT EXCHANGERS (Sterling Thermal Technology Report.,2022)

1. Tantalum
2. Titanium

3. Inconel
4. Zirconium
5. Hastelloy (Sterling Thermal Technology Report.,2022)

MATERIALS FOR HIGH TEMPERATURE HEAT EXCHANGERS

1. Ferrite steels
2. Advanced silicon carbide and carbon composites
3. Nickel-based alloys e.g. Hastelloy and Inconel

Hastelloy is an alloy which includes nickel and is best favored for its corrosion resistance and good temperature resistance. It is easy to manipulate and weld. It is ideal for chemical plants.

Inconel falls in a family of nickel-chrome based super-alloys. Inconel 625= 65% nickel, 22 % chrome, 9% molybdenum, 4 % niobium. It is suitable for high temperature plants like CSPs. It resists cycling.

Tantalum is a rare material with a melting point=2 850 °C.

Titanium heat exchangers are used for aerospace.

Zirconium heat exchangers are corrosion resistant. They are malleable and strong. They withstand high pressure and high temperatures e.g. in CRT CSPs (Sterling Thermal Technology Report (2022))

<u>MATERIAL</u>	<u>MELTING POINT</u>	<u>BOILING POINT</u>	<u>DENSITY</u>	<u>Cost per kg</u>
Tantalum	3 020 °C	5 457 °C	16.6 Mg/m ³	
Titanium	1 668 °C	3 287 °C	4.5g/cm ³	
Inconel	2 277 °C	3 000 °C	8.17 g/cm ³	
Zirconium	1 855 °C	4 409 °C	6.49Mg/m ³	
Hastelloy	1 327 °C	-	8 890 kg/m ³	
Ferrite steels	1 538 °C	-	-	
Silicon Carbide	2 730 °C	sublimes	3.21 g/cm ³	
Carbon composites				
Stainless steel	1 530 °C	1 425 °C	8 000kg/m ³	
Copper	1 085 °C	2 562 °C	8.96 g/cm ³	US\$8.25
Duplex	1 440 °C	-	7.8 g/cm ³	
Super Duplex	1 350 °C	-	7.8 g/cm ³	
Monel	1 300 °C	-	8.8g/cm ³	US\$0.0398
Cupronickel	1 867 °C	-	8.94g/cm ³	US\$7.95
Carbon steel	1 425 °C	2 900 °C	7 850 kg/m ³	
Admiralty brass	-	-	85.25 kg/m ³	
Aluminum brass	660 °C	-	-	
Aluminum	660 °C	2 470 °C	2.7 g/cm ³	US\$3.6 PER kg
Brass	930 °c	1 100 °C	8.73g/cm ³	
Diamond	3 550 °C	4 830 °C	3 630 kg/m ³	US\$60 Million

TABLE 8

METAL	THERMAL CONDUCTIVITY(W/M-K)	COMMENTS
Diamond & or Graphite	2000	Highest heat conductivity
Silver	429	Smoker's experience is its disadvantage
Copper	398	It is corrosive resistant and normally used in manufacturing industrial heat exchangers
Aluminum	237	It has Light weight
Brass	147	
Zinc	112	
Copper Brass	111	
Aluminum Bronze	76	
Wrought Iron	59	
Carbon Steel	51	
Lead	35	Cannot be considered for heat exchangers
Stainless Steel	16	Used for to manufacture Thermal Energy storage Tanks because of its low thermal conductivity
Nickel	97.5	Cannot be considered for heat exchangers

Table 9 Prepared with the assistance of Industrial Metals (2019), Heat Conductive Materials

The above table points to the fact that only diamond, silver, copper and aluminum can be considered for manufacturing Heat exchangers because of their high thermal conductivities. Diamond is prohibitively expensive. The paper recommends copper because of its more attractive corrosive resistance. From the above table it can be seen that diamond or graphite are the best materials to use as heat exchangers in the boiler (HTF to water) and the condenser (steam to water) because of their superior strength and astronomically high thermal conductivity. The paper therefore would

have recommended heat exchangers made from diamond and graphite, but diamond is very expensive so graphite heat exchangers are recommended from above.

The paper posits that all metals are good conductors of heat but differ in their capabilities of doing so. The working fluid normally used in Concentrated Solar Power(CSP) plants of the Central Receiver tower is water which is converted to high pressure, super-heated steam to drive the power block (i.e. turbine & generator unit).

For a solar absorber to be effective the aggregated surface area for the heat source (Heat Transfer Fluid-molten salt) and the heat destination (Working Fluid(water)) must be large on both sides for efficient heat transfer. The heat exchanger must be thin but have high mechanical strength so that no heat is wasted in the heat exchanger. Heat exchangers are rated according to their heat transfer efficiency from the Heat Transfer Fluid and the working Fluid.

It is a fact that heat insulators cannot be considered for manufacturing heat exchangers, but where the heat exchanger is exposed to the atmosphere if it's there, it must be insulated. All pipes of flow for HTF and working Fluid(WF) must be insulated on the outside to prevent thermal energy loss to the atmosphere or surrounding.

Good electrical conductors like metals are also good thermal conductors and good electricity insulators like porcelain, asbestos, glass are also good thermal energy insulators.

1 Watt=1 Joule per second

$m c \Theta + \text{power block losses (heat engine losses)} = 100 \text{ MW}$

where m = mass of steam leaving the boiler per second

c =specific heat capacity of water

Θ =temperature difference between steam to boiler (heat before exchanger) and temperature of steam leaving boiler (temperature after heat exchanger).

The following equations hold true in the boiler or condenser

$$\frac{n_1 P_1 V_1}{T_1!} = \frac{n_2 P_2 V_2}{T_2!}$$

Where n_1 =number of moles of the Heat Transfer Fluid

P_1 =Pressure of heat Transfer Fluid(HTF)

V_1 =Volume of HTF

T_1 =Temperature of HTF

N_2 =number of moles of the working Fluid

P_2 =Pressure of the working Fluid(WF)

V_2 =Volume of Working Fluid

T_2 =Temperature of working fluid

Enthalpic content of the Working Fluid=power station rating plus losses from the boiler to generator output

Types of Heat Exchangers

(a) Pipe-in-pipe heat Exchangers

2 pipes with different diameters inserted one pipe inside the other! This is assisted by coiled clutch couplings. Counter-flow ensures maximum heat transfer e.g. 4m long. The efficiencies of these exchangers is normally 70 %.

Advantages

- The coolant has high flowrate which is achieved by proper selection of the diameters of the pipes.
- Ease of maintenance
- Versatility-possible to use both liquid and vapor (Edrels and Petrov., 2020)

Disadvantages

- Large size
- High cost

- It is difficult to design

(b) Tube-and-shell heat exchangers (Edrels and Petrov., 2020)

Advantages

- Reliable internally-resistant to scale formation implying less frequent cleaning
- Long service life

Disadvantages

- Large dimensions
- The outer part of the case is vulnerable
- The 70 % efficiency result in increase in energy losses

(c) Plate heat exchangers (Edrels and Petrov., 2020)

The heat exchangers are made of stainless steel with copper pipes. The efficiency is high i.e. 95%. Compactness is the result

Advantages

- Has higher efficiencies
- Compactness
- The cost depends on the number of plates installed in it.

Disadvantages

- The service life is short. They are quickly clogged. Maximum life without cleaning is 3 years.

d) Spiral Plate Heat Exchangers (Edrels and Petrov., 2020)

Advantages

- Counter-flow which results in very low pressure drop

Disadvantages

- Limited number of manufacturers because of patents
- Costlier compared to other kinds of heat exchangers

(e) Spiral tube Heat exchangers

Advantages

- Compactness
- Inexpensive
- Low power
- Can accommodate high pressures (Edrels and Petrov., 2020)

Disadvantages

- Limited number of manufacturers because of patents (Edrels and Petrov., 2020).

Heat Exchanger(HEX) Classification by Flow Configuration

There are 4 basic classes

1. Counter flow
2. Concurrent flow (parallel flow)
3. Crossflow
4. Hybrid such as counter flow, crossflow and multi pass flow

COUNTER FLOW

Fluids flow in opposite direction and also in parallel to each other. It achieves the largest temperature change in both fluids per unit time (Brogan., 2011). It is the most efficient heat exchanger.

COCURRENT FLOW

The streams flow in parallel and also in the same direction. It is less efficient than the counter-flow (Brogan., 2011).

CROSSFLOW

Are in between in efficiency between counterflow and parallel flow exchangers. The streams flow at right angles to each other (Brogan., 2011).

CATEGORIZATION OF THERMAL EXCHANGERS BY CONSTRUCTION

1. Recuperative
2. Regenerative

In recuperative heat exchangers the flows flow in separate flow paths simultaneously separated by a wall of an appropriate material.

In regenerative heat exchangers the path is same and single in which cold and hot fluids pass alternatively through in time-time division multiplexing i.e. share the channel in the time domain. Regenerative thermal exchangers are also called Capacitive heat exchangers.

There exist 2 types of Regenerative heat exchangers namely (1) static and (2) dynamic (Brogan., 2011).

There exist three kinds of recuperative thermal exchangers as follows: -

1. Indirect contact
2. Direct contact
3. Specials

In indirect contact heat exchangers, the fluids that exchange heat are separated by employing tubes or plates.

In direct heat exchangers fluids that are exchanging heat are not separated and rely on close contact of the fluids (Brogan.,2011).

The use of fins in a smooth tube or channel avails the best overall performance for heat exchangers (HEX). Vortex generator greatly enhances the rate of thermal energy transfer and minimizes pressure drop.

A helically baffled thermal exchanger (helix changer) is a type of shell-and-tube exchanger. Multi-stream thermal exchangers also increase heat transfer efficiency.

TUBE & SHELL HEAT EXCHANGER

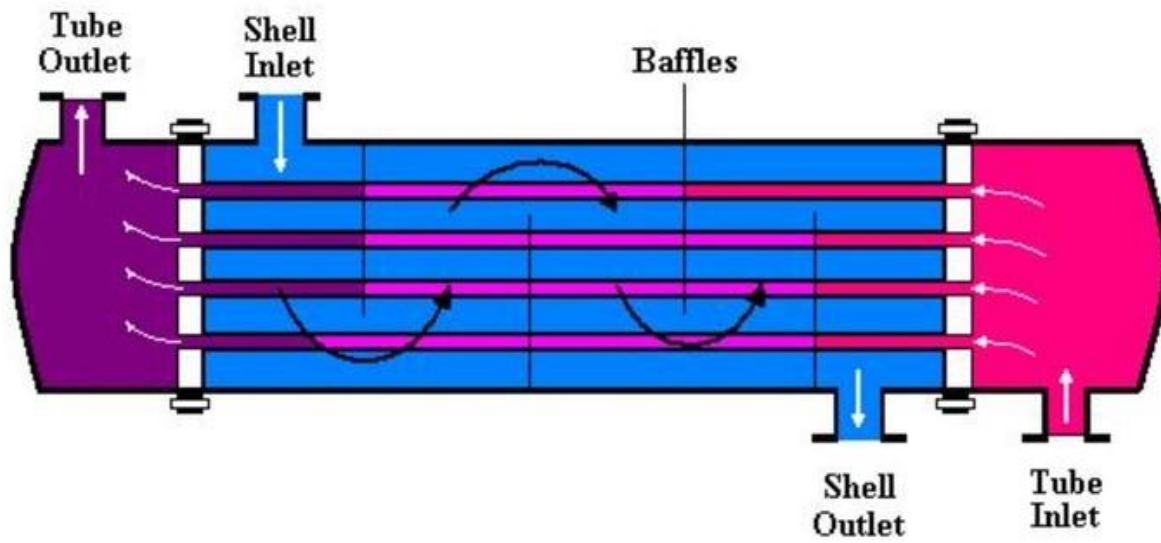


Figure 59

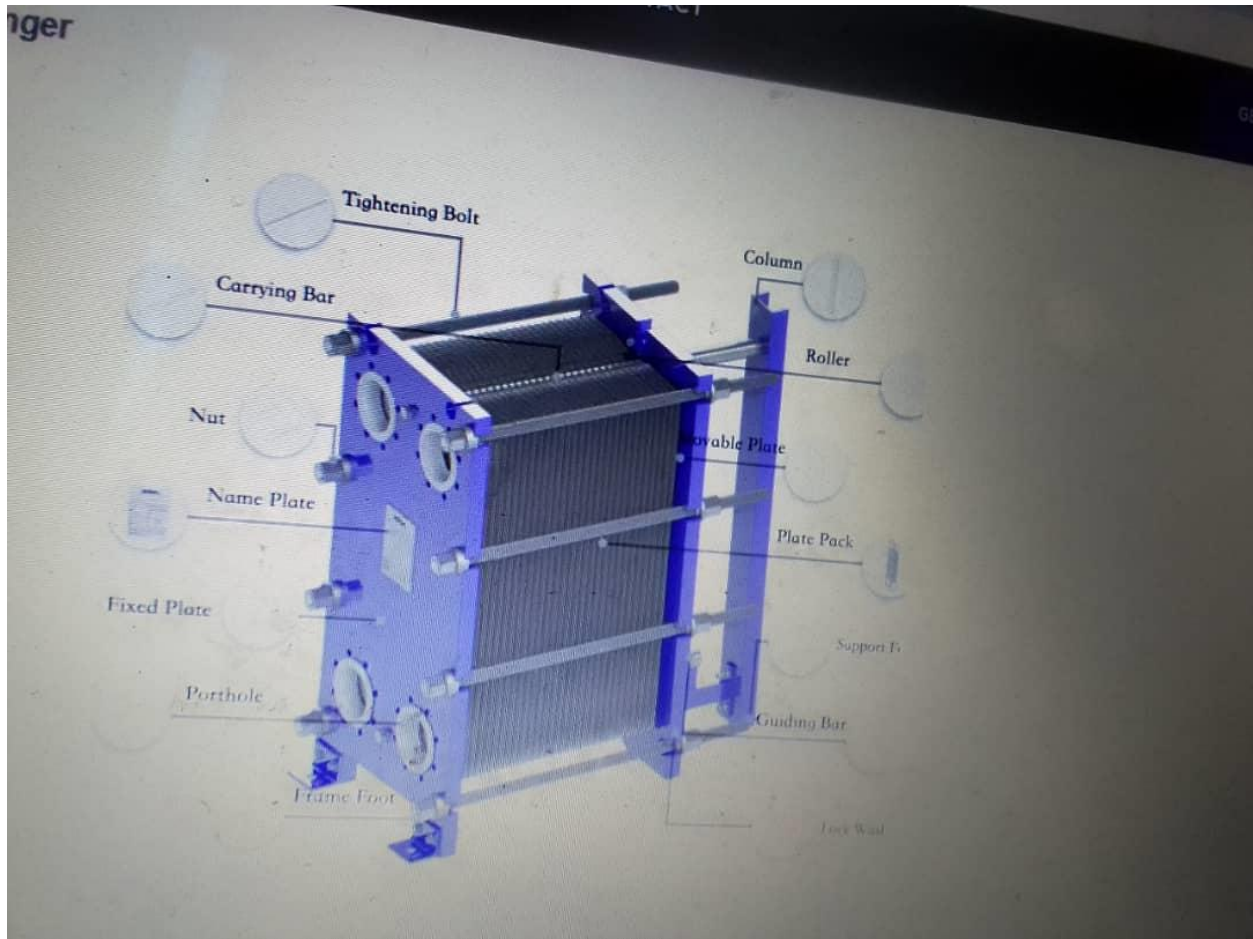


Figure 60 : PLATE HEAT EXCHANGER

Graphite Heat Exchanger



Figure 61 :Suitable for a wide range of chemical heating, cooling and condensing applications

Impervious graphite is a good conductor of thermal energy and could be employed to manufacture thermal exchangers.

Alternative Classification of Thermal Exchangers

- Shell and Tube thermal exchangers
- Finned tube thermal exchangers
- Graphite thermal exchangers
- Thermowave thermal exchangers
- Parallel flow heat exchangers
- Counter flow thermal exchangers.

Dimensioning of the Thermal Exchanger

Specific heat capacity of steam =996 Kj/kg –K

1 s= 500 MW=500 MJ

Mass of steam leaving the heat exchanger per second=
$$\frac{500\,000\,000\,W}{996\,000 \times 465} = 1\,080\,kg$$

Density of steam= 0.8 kg/m³

Therefore volume of steam leaving the heat exchanger per second=
$$\frac{1\,080}{0.8} = 1\,350\,m^3$$

Volume of steam leaving –volume of water entering the heat exchanger. Need to consider the conductivity of the material used to manufacture the heat exchanger.

Volume of heat exchanger must be more than 3 times the volume of steam leaving the exchanger per second=1 500 m³.

McΘt=500 x 10⁶ W, where c=4200 J/g- K, Θ= (1000-20) °C= 980

t=0.09sec

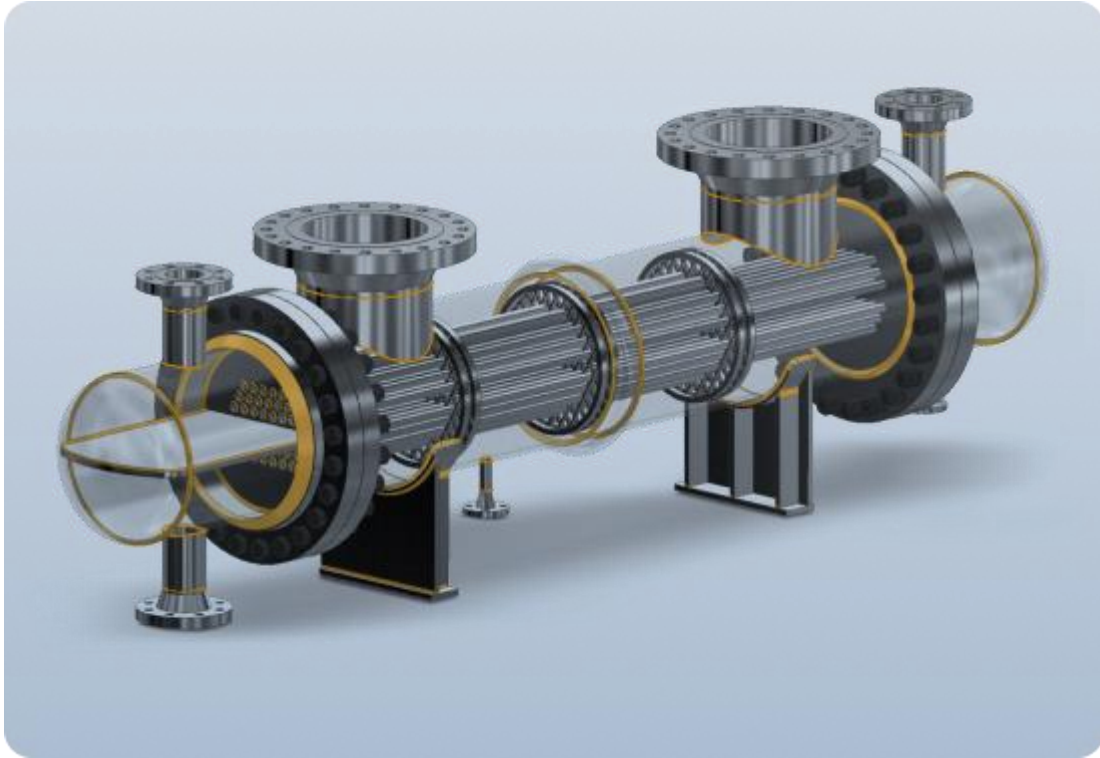


Figure 62

According to Sobban et.al./ (2024), The performance of heat exchangers can be enhanced by a twisted tape insert in the holes compared to straight pipes. The twisted tape also increases pressure drop.

Area for Future Research

(1) How to make heat exchangers more efficient?

SIZING A HEAT EXCHANGER FOR A 500 MW CENTRAL RECEIVER TOWER POWER PLANT USING MOLTEN SALT AS A THERMAL ENERGY STORAGE FLUID AND WATER AS THE WORKING FLUID

In order to determine the size of a heat exchanger to produce 500 MW, we need to consider the two fluids to give us the total volume of the heat exchanger.

The energy in molten salt is given by or equal to $mc\Theta$ where m =mass required to generate 500 MW, c =specific heat capacity of molten salt specifically potassium nitrate and Θ is the rise in temperature from ambient to final temperature considered to be 565 °C.

$$Mc\Theta=500 \text{ MW}$$

$$\text{Specific heat capacity of potassium nitrate}=1.118 \text{ J/g } ^\circ\text{C}$$

$$\text{And we are saying } \Theta=(565-20) ^\circ\text{C}=545 ^\circ\text{C}$$

$$Mc\Theta=500 \text{ MW}$$

$$M \times 1.18 \times 545 = 500 \text{ MW}$$

$$643.1 \text{ m J} = 500 \text{ MW}$$

$$1 \text{ Joule} = 1 \text{ Watt}$$

$$1 \text{ MW} = 1 \text{ MJ}$$

$$643.1 \text{ MJ} = 500 \text{ 000 000}$$

$$m = \frac{500 \text{ 000 000}}{643.1}$$

$$m = 777 \text{ 484.06}$$

$$m = 777.484 \text{ kg}$$

$$\text{Density} = \frac{\text{mass}}{\text{Volume}}$$

$$\text{Volume} = \frac{\text{mass}}{\text{Density}} +$$

Volume of potassium nitrate=777.484/

Therefore, mass of potassium nitrate to generate 500 MW=778 APPROXIMATELY

Density of potassium nitrate=2.11 g/cm³

$$\text{Volume} = \frac{778}{2.11} = 369 \text{ m}^3 \text{ approximately}$$

Considering Water which is our working fluid which gets heat from the heat exchanger

$$Mc\Theta = 500\,000\,000 \text{ W}$$

Specific heat capacity of water=4.2 J

$$\Theta = (565 - 20) = 545 \text{ }^\circ\text{C}$$

$$4.2 \times 545 \times m = 500\,000\,000$$

$$m = 218\,435.998 \text{ g}$$

$$m = 219 \text{ kg}$$

$$\text{Volume} = \frac{\text{mass}}{\text{density}} + \frac{218435.998}{1000} = 218.435998 \text{ m}^3$$

Therefore, total volume of the heat exchanger=volume of potassium nitrate+ volume of water

$$\text{Total Volume of the heat exchanger} = 218 + 369 = 589 \text{ m}^3$$

If we assume the length of the heat exchanger=10m

$$\pi r^2 h = 589 \text{m}^3$$

$$\pi r^2 \times 10 = 589 \text{m}^3$$

$$r^2 = \frac{58.9}{\pi}$$

$$r = 4.3 \text{m}$$

Density of water = 1000 kg/m³

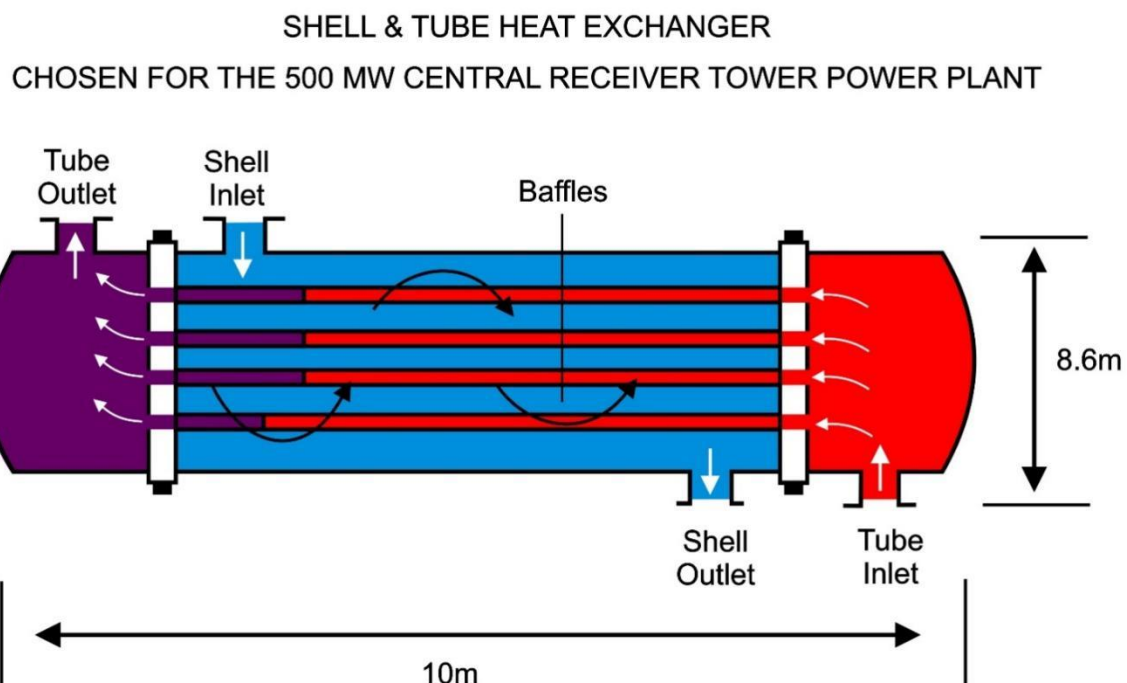


Figure 63

The surface areas of the heat exchanger that is exposed to the atmosphere has to be fully covered by a heat insulator such as pyrogel aerogel blanket insulation to prevent heat loss to the atmosphere.

Key Assumptions

- (1) The heat exchanger once commissioned will remain functioning forever. In practice the heat exchanger may develop faults

Conclusions

A thermal exchanger which is also called a heat exchanger is an indispensable part of a Central Receiver Tower power plant. There are various materials from which heat exchangers are made from. Thermal energy exchangers can be categorized by configuration as (a) counter flow (b) parallel flow (c) cross flow and (d) hybrid. They can also be classified as (a) pipe in pipe (b) shell and tube (c) plate (d) spiral plate and (e) spiral tube.

For this project the shell and tube type of heat exchanger for a 500 MW Central Receiver Tower type Power Plant was designed having a length of 10m and a diameter of 8.6 m

The project now proceeds to design the condenser for the 500 MW CRTTP

3.8 DESIGN OF A CONDENSER FOR A 500 MW CENTRAL RECEIVER TOWER POWER PLANT

INTRODUCTION

This section highlights that a condenser is a key part of any thermal energy station. It analyses the function of a condenser in a heat power station also called a thermal power station, the processes which occurs within the condenser are analyzed as well as good characteristics of condensers are discussed. The advantages of using a condenser are investigated and proffered. The condenser is posited as being not only a critical, vital and important component, but also necessary and indispensable part of a thermal power plant. The section highlights that the major duty of a condenser is the conversion of steam from the turbine into water which is then pumped by an electric pump back to the cold thermal storage tank or receiver. It provides a transition from a pneumatic system to a hydraulic system involving the working fluid that is usually water.

The section posits that the condenser enhances the heat efficiency and therefore the overall efficiency of the thermal power plant. In the process it also reduces plant operational costs by reducing the water cleaning burden since the condensate is already clean. When steam condenses to water there is a reduction in volume of about 1600 times which creates a vacuum in the extra space thereby creating suction forces in the turbine or back pressure.

Different types of condensers are scrutinized including materials they are made from. The heat exchanger tubing carrying the cooling water needs to present, avail and provide adequate surface area for efficient heat exchange. It must be an excellent conductor of heat i.e it must possess a high thermal conductivity.

The three activities within a condenser are de-supeheating, condensation and subcooling. The paper posits that the boiler or thermal exchanger converts water to water vapor or steam and the condenser does exactly the opposite of that i.e. converts steam to water. This completes the water-steam-water cycle.

The section concludes by highlighting areas for future research and summarizes research findings.

Methodology

Research is broadly classified into two categories namely experimental and non-experimental. This paper concentrated on non-experimental research. Among the non-experimental research are methods such as observational research, archival research as well as Case study research. The author used archival research whereby journals from google scholar, dimensions and scopus were consulted and supported by general internet research. Articles on power station condensers were given more weight than condensers for refrigeration and automobiles. No textbooks were specifically consulted for condensers except for the general understanding of thermal power stations as background study. Ethics in research were adhered to in that reference material were also cited within the main text and plagiarism was kept at a minimum whilst every effort was made to totally eliminate plagiarism. The instruments used in the research were fairly valid and reliable in that journals undergo through rigorous review before publication.

MAIN NARRATIVE

As world population increases, so does demand for energy. As demand for energy increases the world demand for thermal power stations and therefore condensers also skyrockets. The pressure that arises when water is converted to steam due to the adiabatic expansivity of steam ($\times 1600$ times) creates huge pressure needed to produce the needed torque to produce rotational kinetic energy of the prime mover (turbine)-generator set. If there is no condenser the boiler will be full of steam only and therefore no pressure due to the volumetric expansion caused by the change of state from liquid water into gaseous water vapor that is needed to rotate the turbine. Therefore, the condenser is indispensable in order to convert steam to water. The heat exchanger in the boiler converts water to steam.

Problem Statement

Thermal power stations including nuclear, fossil fueled and solar powered all require condensers to operate. Knowledge about condensers need to be amplified within the

engineering community and there are few literatures materials about this critical component available.

Research Questions

1. What are the functions of a condenser in a thermal power plant?
2. What materials are the thermal condensers made from?
3. What processes occur in a condenser

Research Objectives

1. To highlight the functions of a condenser.
2. To identify materials from which condensers are made from.
3. To briefly discuss processes which occur in a condenser.

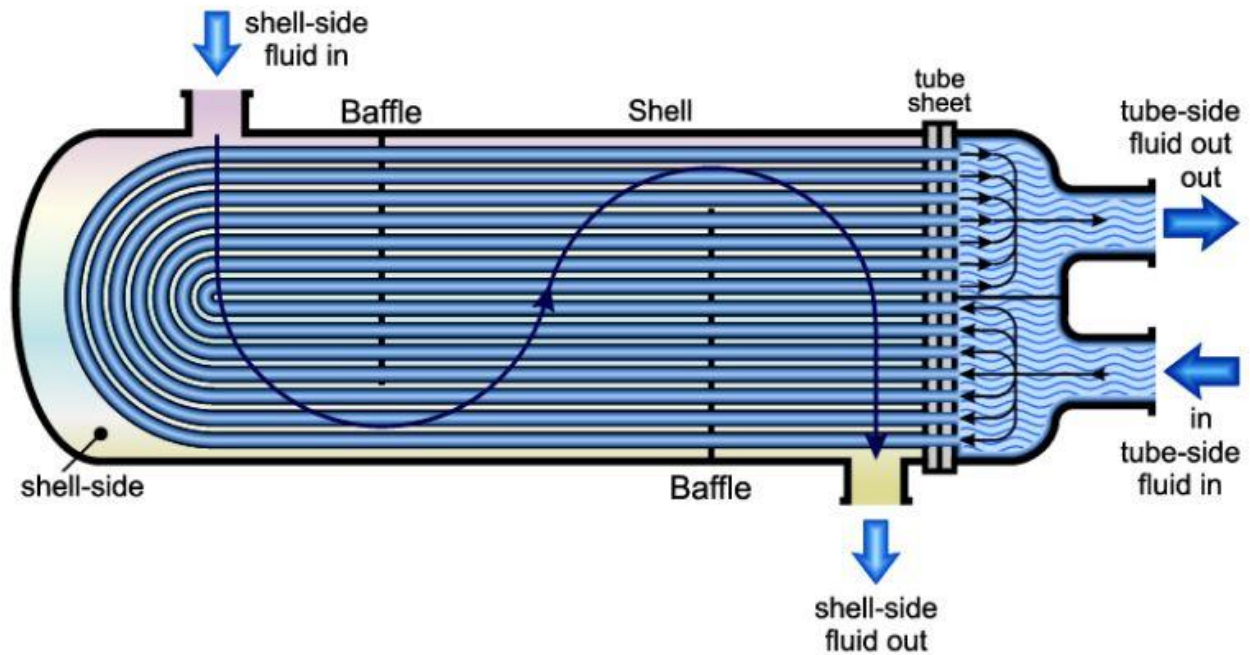


Fig 64 A picture of a condenser

The following are the reasons why condensers are needed in a Thermal Power Plant: according to NeoNickel report (2024): -

1. To condense steam into water
2. To maximize the power station's efficiency
3. To produce steam condensate and recycle water that can be reused in the receiver as feed-water thereby promoting efficient utilization of this resource.

Moore (2017), says that in conventional thermal power plants, steam condensers play a critical and important role. According to WTS Energy report (2024), once steam is directed via the prime mover (i.e. turbine), the water vapor is sent to a condenser. In order to convert super-heated steam to subcooled water, a secondary cooling liquid is required. Ha et al. (2011), says steam turbines and condensers require a lot of water. According to Ha et al. (2011), the turbine is rotated by high pressure steam at about 100-200 atm. and a high temperature of greater than 500 °C. Mishra and Arya (2015) posits that routing of steam from the turbine to the

condenser is necessary in order that heat may be rejected to the atmosphere via finned tubes. Moore (2017) says that steam power plants operate on the Rankine cycle. Moore (2017) highlights that the Rankine cycle involves four main components namely pump-boiler-turbine-condenser. The turbine or prime mover is driven by steam. It is a transducer that converts thermal pressure energy to rotational kinetic energy.

According to Moore (2017), after the steam from the prime mover also called the turbine is condensed by the condenser, it is passed on to the cold thermal energy storage tank or receiver by pumps if water is used as both thermal energy storage fluid and working fluid. In this project molten salt is used as the thermal energy storage fluid and water is only used as the working fluid. The condenser is needed to reduce the outgoing pressure of the super-heated steam to below atmospheric thereby increasing the turbine and therefore power plant efficiency. The other advantage of the condenser according to Moore (2017), is that it provides a source of clean and pure water to the receiver/heat exchanger preventing scaling and reduced capacity since the condensate is a byproduct of pure distillation.

According to Zafar (2017), a condenser is defined as a closed container or vessel whereby steam is condensed by abstracting the thermal energy from the steam and pressure is maintained below atmospheric pressure. Areaacademy report (2023) says that a condenser is a gadget employed to convert superheated steam into water.' The WTS Energy report (2024) highlights that a condenser is a large heat exchanger that employs cool water for condensation of steam back to water. According to U.S. Nuclear Regulators' Commission (2021), a condenser is a big heat exchanger designed or meant to cool exhaust super-heated steam from a turbine so that it can be returned to heat source as water. The WTS Energy report (2024) again defines a condenser as a power plant component that converts steam into liquid water. Heat extracted from steam in the condenser is sent to some circulating water and is rejected to the environment or atmosphere either through a body of water or a cooling tower. The cooled water is then sent to the cold thermal energy storage tank for onward transmission to the receiver or directly to the heat exchanger. A condenser converts vapor into liquid through a process of extracting heat e.g. from superheated steam until it condenses to a high pressure saturated water from a high

pressure steam. The cooling from super-heated steam to condensation temperature is called desuperheating. Areaacademy report (2024), highlights that the cooling of heated steam to temperatures below condensation is called subcooling. Desuperheating, condensation and subcooling are the three major functions of a condenser. According to U.S. Nuclear Regulators' Commission report (2021), the other function of the condenser is to facilitate flow to the expansion valve. The WTS Energy report (2024), posits that the condenser greatly enhances the power plant efficiency. The otherwise lost heat to the environment is instead recycled back to the plant's generating activity.

The WTS Energy report (2024), says that the superheated steam goes into the condenser with temperatures being higher than saturation temperature. The steam is desuperheated by the front end of the condenser to temperatures of saturation. According to WTS report (2024), 15 % to 25% of total heat is rejected during this phase.

After attaining saturation temperature, latent heat is lost during condensation and about 70% to 80% of heat is rejected during this phase of condensation. Latent heat of condensation is rejected during this process. Condensation is a constant temperature process.

The thermal energy released from the superheated steam, heats the secondary medium i.e. water whose temperature therefore increases. The differential temperature between outlet and inlet of the condenser is big and thermoelectric generation may be implemented here. The greatest pressure drop occurs during desuperheating. In the condenser, the velocity of flow of the refrigerant is made less as the superheated steam condenses.

When we compare counter-flow and co-current flow, counter-current flow is preferred in condensers. There is need to evacuate the system at the start to prevent inert gases becoming present in the system.

DESUPERHEATERS

Another name for desuperheater is recuperator. It operates by using the high pressure superheated steam temperature to heat water. (15 to 20 % of the total thermal energy

of rejection). The leaving steam temperature is up to a few degrees Celsius above condensation temperature. There are some notable advantages of using a separate desuperheater.

CONDENSATION

Condensation is the reverse of boiling (Serth (2007)). Condensation occurs in the middle part of the condenser when temperatures remain almost constant from a few degrees above condensation temperature to a few degrees below condensation.

CONDENSATION LEVEL CONTROL

According to WHO Industrial report (2024), the most valuable component of the condenser is the cooling tube. A solenoid valve put in the condenser line normally does condensate level control.

SUBCOOLING

After all the superheated steam has been converted to water, subcooling occurs in the lower part of the condenser. Thermal energy transferred is smaller than in the desuperheating and condensation phase. Subcooling is necessary to ensure that no steam exists between condenser and the next component i.e. the cold thermal energy storage tank. After complete and total condensation, subcooling follows and subcooling is a single phase process just like the desuperheating. Condensation is a two phase process i.e. gas(steam) and liquid(water). The WTS Energy report (2024), says that 2-5 % of total heat rejection takes place during this phase of subcooling.

According to Serth (2007), subcooling is the last step before the water is sent out of the condenser. Serth (2007) says that subcooling refers to every degree which the water thermal level falls below the saturation point. The expansion valve is the last place to remove heat from the coolant water before the cycle begins (Serth (2007)).

If higher subcooling is required, it may be necessary that a separate heat exchanger called a subcooler be fitted.

SCALING PROBLEMS

Solubility of calcium sulfate (gypsum, CaSO_4) and CaCO_3 decrease with water temperature rise.

There may develop deposits of the minerals on heated surfaces in a desuperheater – a process called scaling. Scaling impairs heat transfer and capacity of the desuperheater is reduced. Pockets of stagnant water may form, encapsulated by the crust. These water pockets can act as reaction points for corrosion of stainless steel. Soft water has little problems, but if hard water is used precautions need to be taken to minimize the problem of scaling.

According to Ha et al. (2011), scales may cause pipe blockage, severe abrasion and local bursts. Condenser water is distilled water and no impurities except from corrosion of pipe walls.

According to WTS report (2024), three parameters can be manipulated to avoid scaling i.e. chemical properties, turbulence and temperature. Water with no ingredients for scale formation is scale resistant. Turbulent flow diminishes the chances of scaling because the shear stresses can dislodge the newly formed deposits from the surface walls –the self-cleaning effect. Since solubility of calcium sulfate increases with lowering temperature, scales are likely not to form with lower temperatures.

Cleaning in place method can be employed to remove scales.

According to Serth (2007), surface condensers are employed to condense the superheated exhaust steam from turbines.

The Trane report (2024) says that the cooling system has one of two coils called condenser which work together to compliment in the heat exchange cycle. That is where thermal energy is emitted by the steam, and absorbed by coolant water. A condenser has a large metal shell having tubes arranged into rows running vertically and horizontally with finned aluminum coils. The fins enhance the surface area for fast and efficient heat rejection. The condenser coils should be free from debris and dust. The Aftermarket Canada report (2024) says that the condenser is for climate control and must be damage free and leak-free.

A condenser is a vital part of any thermal power station e.g. of the Central Receiver Tower Type. It facilitates transfer or exchange of heat at high temperature from the Working Fluid (WF) to the cooling water circulation system thereby condensing steam to water. The heat-exchanger heated working fluid that generates steam needed to drive a heat engine or power block also the steam needs to be condensed into water. The water-steam-water cycle involving the heat exchanger, condenser and the boiler (receiver) is essential for any thermal power plant and the advantages of a condenser are as follows: -

- The condensed steam is employed as feed water to the boiler i.e. the receiver. This reduces the cost of energy generation as the feed water is at a higher temperature compared to natural and normal water from the environment. The feed water cleaning system's capacity is thereby reduced
- The thermal power plant's efficiency is increased due to the vacuum in the condenser which increases the enthalpy drop. Steam consumption by the power plant decreases as the presented enthalpy drop or work produced per kg of steam increases with the diminishing back pressure by using the condenser.
- Salt deposition in the boiler is avoided with the employment of condensate instead of using feed water from alternative outer sources which could possibly contain salt. The deposition of salt in the boiler diminishes efficiency.
- The heat efficiency of the power plant is increased thereby enabling the reduction of the overall cost of generation which results from the use of the condenser.

The cooling circulating water which enables condensation in the condenser is finally circulated in the cooling tower in order to dissipate heat into the atmosphere.

Good Characteristics of a Superior Condenser

- The circulating water must be of minimum quantity.
- Minimal surface area for cooling per Kw capacity.
- Minimal auxiliary power supplies
- Maximum condensed steam per m² of the cooling surface area.

According to NeoNickel report (2024), technical specifications for condensers takes into account operating pressures, operating temperatures, condensing capacity and flow rates.

MATERIALS USED FOR MANUFACTURING CONDESERS

METAL	THERMAL CONDUCTIVITY(W/m-K)
Diamond	2 200
Titanium	11.4
Copper	398
Aluminum	237
Zinc	116
Brass	120
Steel	45
Cupronickel	29

TABLE 10

Janikowski (2007), says that the key properties that need to be considered in selecting materials for condensers include erosion resistance, mechanical and thermal properties, corrosion resistance, cracking potential, vibration potential and temperature limitations. According to Janikowski (2007), the dissolution of the surface of a metal e.g. wall thinning of copper alloys and rusting of carbon steel is called corrosion.

Corrosion is a dangerous process in condensers. It threatens safety and operational efficiency as well as cause damage to equipment. According to NeoNickel report (2024), titanium is the best material for manufacturing condensers as it has corrosive resistant properties. It is a high strength and low density material better than copper nickel alloys. Nowadays copper bearing alloys are rarely used. The above report says that titanium is the best reliable material choice for condenser tubing. Some of the disadvantages of titanium are that it is has high installation costs and costs more.

The oth er material is stainless steel. It is economic and is corrosive resistant.

According to WHO Industrial report (2024), the frequently employed materials for manufacturing condenser are stainless steel, titanium, cupronickel, brass and carbon steel.

BRASS STEEL

Cu-Zn alloy brass tube has good heat transfer and has corrosion resistance when compared to stainless steel tubes. They are not easy to scale. If the flow rate of water rises, it is the preferred material for the pipes of the condenser. There is great corrosion with water with high salt content.

CUPRONICKEL

It has better chemical stability compared with brass. It is corrosive resistant and its price is higher than that of brass.

TITANIUM TUBE

It has high corrosion resistance. It is a high strength and low density material. All titanium welding is necessary.

STAINLESS STEEL

It has excellent mechanical properties and is corrosive resistant and low price and therefore economical. Most condensers use stainless steel.

Advantages of Stainless Steel

1. Cheaper than titanium and copper pipes.
2. Higher strength and hardness
3. High elastic modulus compared with copper and titanium.
4. Higher corrosion resistance
5. Easily available on the market

Copper Alloys have biofouling resistance, has high thermal conductivity and is simple to fabricate.

Surface steam condensers ensures that there is no mixing of exhaust steam and the cooling water. The condensate is reused in the solar absorber. Even water that is impure could be employed for cooling purposes in surface condensers which is not allowed in jet condensers where the water must be pure. The surface condensers require more capital costs and space than jet condensers, but are still preferred because of its low running expenses and high heat efficiency.

In thermal power plant, thermal energy is converted to electricity via steam driven turbines. When water is highly heated it expands into steam thereby generating enough pressure to rotationally turn the turbine-generator set. After turning the turbine, the steam resulting therefrom is condensed back to water and recycled back to the boiler for reheating and evaporation. This constitute the basic and fundamental principle of the Rankine cycle.

According to Zafar (2017), the efficiency of thermal or steam power plants is increased and enhanced by the use of condensers through the process of decreasing the exhaust pressure of steam to below atmospheric pressure. The used condensed steam may also be recovered to avail a source of clean and pure feed water to the boiler that results in a reduced water softening plant capacity by a significant amount.

The pinnacle thermal efficiency of the thermal power scheme is given by: -

$$\text{efficiency}(n) = \frac{T_1 - T_2}{T_1}$$

Where T₁=the supply temperature

T₂=the exhaust temperature

Components of A Condenser.

Types of Condensers (WTS Energy report (2024))

1. Jet condensers

2. Direct contact condensers
3. Surface condensers

Types of Condensers according to McNaught (2011)

- Spray condensers-spraying the coolant into a vessel containing the vapor
- The Baffled Column –coolant directed to ensure that it flows over a series of trays in a column. Counter flow of vapor and coolant. We must avoid flooding and therefore care must be taken.
- The packed column condensers-tightly packed rings of metal to enhance the interfacial for thermal energy transfer's area. Liquid at top of column and vapor at the bottom.
- The jet condenser- A jet of water is directed into stream of steam with the intention of desuperheating the superheated steam. A jet of water injected into pipeline carrying steam via a small bore pipe and a nozzle installed at the center line. Liquid which is water is normally injected in counter-flow to the super-heated steam.
- The surge pipe condensers- a pipe having holes for injecting bubbles of steam into a pool of water.
- Tube and shell condensers
- Condensers of the Crossflow shell side..
- Baffled shell and tube condensers
- Tube side condensers
- Plate type condensers

According to Mishra and Arya (2015), thermal power station condensers may fall in two classes namely (a) Steam condenser or Water cooled condenser and (b) air-cooled condensers.

CONDENSERS THAT ARE COOLED BY WATER

In Steam condenser or water –cooled condensers, heat is absorbed by secondary water. There are two types of water-cooled condensers namely jet condensers and surface condensers.

Jet condensers have the advantage that less flow area is required, require low maintenance costs, low initial costs and less water is required. The disadvantage is that high power is needed for pumping water and the condensate is wasted.

There exists no contact between the cooling water and steam in surface condensers. The advantage is that the condensate can be utilized as feed water, better vacuum formed at the prime mover (i.e. turbine) exhaust and less pumping power is needed. It has the disadvantage that high maintenance costs are incurred, high initial costs and needs a large flow area.

AIR COOLED CONDENSERS

Ambient air is forced over the outside of the tubes. They are very large in power stations and require several acres of land.

Advantages

- Simple installation
- No requirement of fire protection system and no employment of water treatment
- Flexibility as air is everywhere unlike water
- No thermal or chemical pollution of cooling fluids
- Air cooled condensers are more economical than water cooled condensers
- Atmosphere is the heat sink.

PARTS OF AN AIR COOLED CONDENSER (Mishra and Arya (2015))

1. Condenser tower
2. Control equipment for air flow
3. Wind partition walls
4. Heating system for bypassing steam

5. Equipment for removing air
6. Tank for storage of the condensate
7. Condensate pumps
8. Expansion joints and steam ducts
9. Air removal pipes and condensate drain
10. Alarms and control instrumentation
11. Pressure relief device
12. Steam duct condensate drain system

The major auxiliary power consuming appliances in air cooled condensers are fans, motors and pumps.

NeoNickel report (2024) says that condensers can be put in two classes namely (a) Direct Contact Condensers where there exists mixing of steam and cooling water and (b) Indirect contact Condensers which have a conducting boundary e.g. a tube and shell where mixing of cooling water and steam is avoided.

According to Aftermarket Canada report (2024), mostly Occurring Faults in Condenser are: -

- Coolant leaking
- Diminishing coolant
- Debris or deposits in the coolant
- Coolant level diminishing
- Overheating
- Compressor failure
- Wear and tear

As a result, there is need for regular inspections, maintenance of tubes and making sure that the cooling water is in a good chemical state to preserve the cleanliness of tubes. Unless repairs are done, efficiency suffers and the condensers become unreliable.

Cristiani (2005) highlights that fouling is a very big problem for condensers. It happens as a result of microbial growth within pipes. It is the Biofilm growth and settlements of different kinds of living organisms. Biofouling causes loss of efficiency in the condenser, clogging of flow-water circuit pipes and plant reliability

reduction over a period of time. Physical cleaning and chemical dosing may be necessary to reduce microbial growth e.g. use of chlorine, chloride dioxide, peracetic acid and sodium hypochlorite as anti-fouling treatment.

According to Moore (2017), air cooled condensers are not able to maintain performance during windy and very hot periods. Air cooled condensers can replace water cooled condensers.

Serth (2007), says that a condenser's efficiency is normally increased by the attachment of fins to the tubing to speed up heat removal. Usually such use of fans to force air through the fins and carry the heat away is beneficial. The Lennox report (2024), says that the condenser coil is normally manufactured from copper tubing with attached aluminum fins or all aluminum tubing to facilitate rapid heat transfer.

According to North West University Boloka Institutional Repository report (2014), the thermal efficiency of a thermal power station can be reduced by loss of condenser backpressure. Loss of condenser backpressure can be caused by (a) fouling (b) pumps not performing (c) ejector not performing (d) air ingress and (e) low cooling water flow.

Al-Mubaddel et al. (2021) says that the 2nd law performance of a condenser increases with rise in thermal conductivity and decreases with rise in fouling resistance and falls with increase in condenser pressure at the tube outlet. Better tube materials increase the overall heat transfer coefficient by up to 6 % (Al Mubaddel et al. (2021)).

According to TEPCO (2024), condensers possess 40 000 to 50 000 pipes for cooling with a thickness of approximately 3 cm through which water flows, operating or working to make the steam cool.

DIMENSIONING OF THE CONDENSER

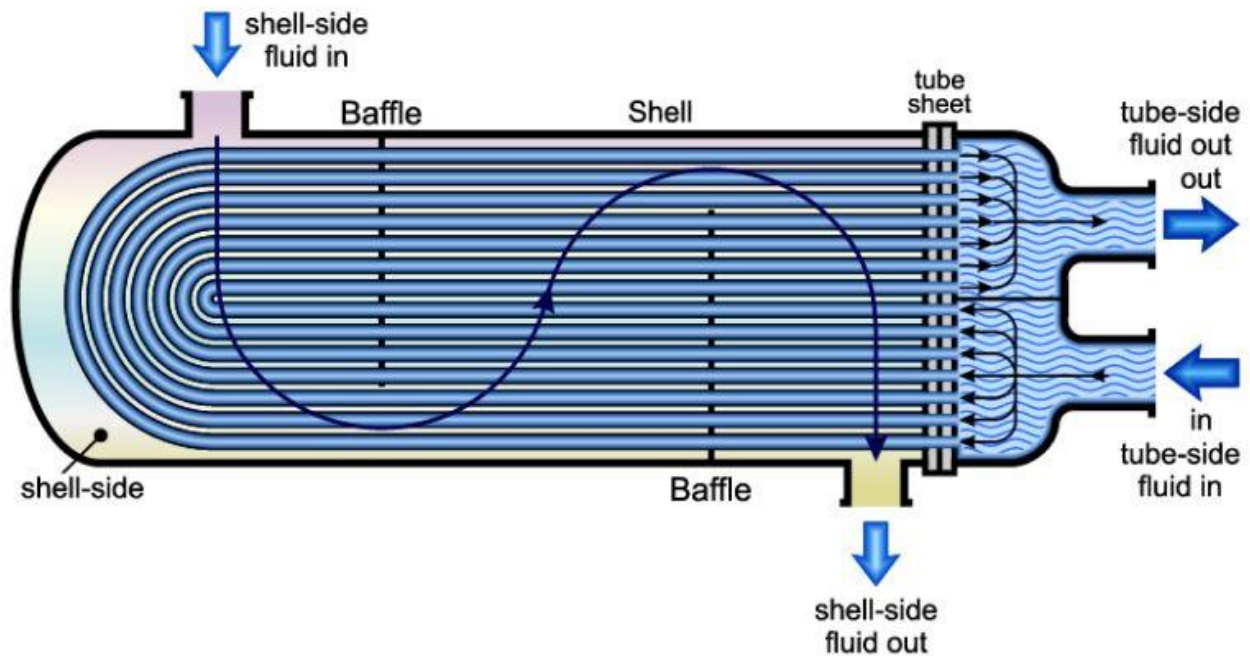


Figure 65

The heat extracted from hot steam= 500 MW= $mc\Theta$

Where: - $\Theta = 565^{\circ}\text{C} - 20^{\circ}\text{C}$ (steam operating temperature-ambient temperature)

$\Theta = 545^{\circ}\text{C}$

m =mass of steam in condenser

c =specific heat capacity of water= $4\,200\text{ W /m}^3$

$$m (4\ 200) \times (545) = 500\ 000\ 000$$

$$m=219\ \text{kg}$$

The amount of steam must be equal to the amount of cooling water from the Cooling tower=219 kg

$$\text{Density of steam}=0.6\ \text{kg/m}^3$$

$$\text{Volume of steam in the condenser} = \frac{\text{mass}}{\text{density}} = \frac{219}{0.6} = 365\ \text{m}^3$$

$$\text{Density of water}=997\ \text{kg/m}^3$$

$$\text{Volume of water} = \frac{\text{mass}}{\text{Density}} = \frac{219}{997} = 0.22$$

$$\text{Total volume of steam \& water in the condenser} = 365 + 0.22 = 365.22$$

$$\text{Volume of condenser assuming cylindrical} = \pi r^2 h$$

Assuming a 10 m long condenser, $h=10$ in above equation

$$\pi r^2 \times 10 = 365.22 \text{ which is approximately } 366\text{m}^3$$

$$r^2 = \frac{366}{\pi \times 10} = 12\ m^2$$

$$r=3.4 \text{ m}$$

Therefore, diameter of condenser=6.8m

DIMENSIONS OF A CONDENSER FOR A 500 MW CENTRAL RECEIVER TOWER POWER PLANT

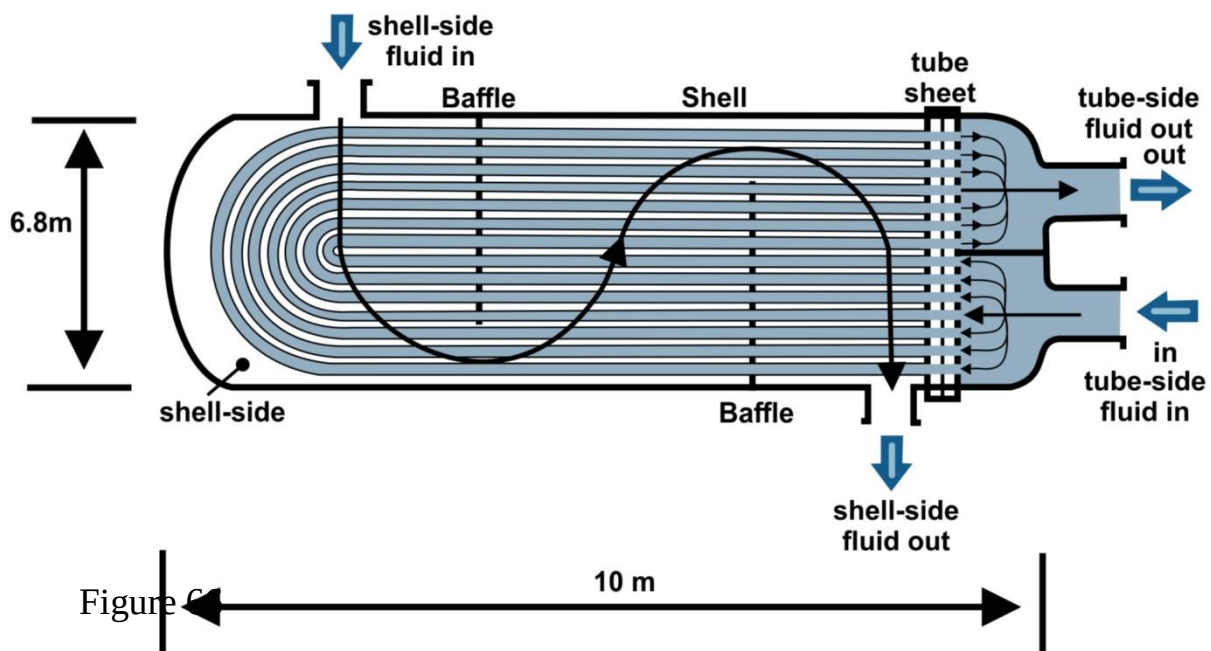


Figure 6

APPLICATIONS OF CONDENSERS

1. In refrigeration
2. In room air conditioning
3. Car radiators
4. In power plants and
5. In distillation

AREAS FOR FUTURE RESEARCH

1. How to enhance the condenser's efficiency e.g. employment of diamond and graphite?
2. What are the best materials for use in the manufacture of condensers?

Key Assumptions

1. The condenser will remain functioning forever. In practice the condenser may need maintenance.

CONCLUSIONS

A condenser is an essential part of a thermal power plant. Condensation occurs when a vapor or gas is converted to a liquid through cooling from which the name is derived. There are two main kinds of condensers namely air cooled condensers and water cooled condensers. The growth of microbial organisms in pipes of the condenser is called fouling which can be prevented by chemical dosing with chlorine and other chemicals. There are three main processes that occur in a condenser namely desuperheating, condensation and subcooling which occurs one after the other in that order. Condensers are required in order (a) to condense steam into water (b) to maximize the power station's efficiency (c) to produce steam condensate and recycle water that can be reused in the receiver as feed-water thereby promoting efficient utilization of this resource. Condensers tubes are made brass, cupronickel, titanium and stainless steel.

The thesis now proceeds to discuss and design the turbine and size the generator for the plant.

3.9 TURBINE DESIGN

TURBINE DESIGN

INTRODUCTION

This part of the project is about designing a turbine and also partly the generator of a 500 MW Central Receiver Tower Power Plant. The section posits that a turbine is an important and essential component of most power plants e.g. nuclear power plants, hydro-power plants and fossil fuel power plants as well as solar thermal power plants. The turbine converts the steam's or water's linear kinetic energy to the turbine or generator's rotational mechanical energy. It is the reverse of an air fan in that while an air conditioning fan converts electricity to rotational motion of the fan, the turbine-generator set converts rotational kinetic energy to electrical energy. The section posits that the area and the number of the blades hit by the steam's pressure is critical in enhancing the turbine's efficiency and rotational speed. The section concludes by saying a 500 MW power tower power plant requires a 500 MW turbine and a 500 MW generator!

MAIN NARRATIVE

According to Omosanya et al. (2019), steam power plants contribute 80 % of worldwide generated electricity. Steam power plants require turbines to operate. Omosanya et al. (2019), posits that the overall efficiency of steam power stations is normally lower than hydro. Chaibakhsh and Ghaffari (2008) says that efficiency and cost considerations have resulted in wide-scale use of steam turbines. Chaibakhsh and Ghaffari (2008) further highlights that a turbine comprises of three stages, high pressure stage, intermediate pressure stage and low pressure stage. A turbine transforms the pressure of moving fluid into mechanical rotational kinetic energy of the generator thereby resulting in the production of electricity. Balaji et al. (2016) says that a steam turbine is a prime mover in which rotary motion results from gradual change of momentum of steam. According to Enel report (2024), a turbine converts steam energy in the form of kinetic into energy of rotation of turbine-generator set. Bennauer et al. (2024), says that a steam turbine is one energy

conversion link among others needed to generate electricity. The Coal Handling Plants report (2024), highlights that a steam turbine is a rotating machine that use steam at high pressure that hits the blades to cause rotation. Kareem et al. (2018) posits that a turbine is a prime mover that transforms energy in the form of kinetic into super-heated water vapor into energy in the form of rotational mechanical through reaction or impact of steam against the blades. Balaji et al. (2016) posits that the superheated steam accesses the steam turbine via the governor valves. The blades are installed onto the rotor of the turbine. The Coal Handling Report (2024), says that the heat exchanger transfers heat to water to become superheated steam. The superheated steam is then directed to the turbine under high pressure. The turbine then drives the generator. After passing via and driving the turbine, the exhaust steam is sent to the condenser. The Enel report (2024) says that the turbine is capable of converting 90 % of steam's kinetic energy into mechanical energy.

A turbine possesses blades which are usually exposed to moving steam that will be under pressure resulting in the turbine drum rotating. The turbine is normally bolted or connected through a gearbox to a generator that transforms the rotational kinetic energy to electrical energy.

A prime mover or turbine is an indispensable, essential, vital or critical part of all thermal power plants including Concentrated Sola Power (CSPs) plants. The alterations in momentum of the moving steam hitting the turbine blades is opposite and equal to the changes in momentum of the turbine-generator set in its trajectory of rotation.

Being connected to a generator, it passes on the rotational kinetic torque or energy to the generator resulting in production of electrical energy. According to Yadav (1972), the principle of operation of a turbine is foundationed on Newton's second law of motion which states that the force is proportional to the rate of change of momentum. The turbine is made of many vanes or blades attached to a rotor which changes the speed and direction of the working fluid. Yadav (1972) posits that the working fluid achieves high velocity as a result of nozzles or fixed blades and changes direction when it impinges on the blades due to the curvature of the blades. Yadav (1972) says that three quarters of electricity generated worldwide is produced by means of turbo-generator. Yadav (1972) emphasizes that the function of a prime mover or turbine technology is to ensure extraction of maximum amount of energy from the working fluid to transform it to valuable work with maximum efficiency, by means of a plant possessing minimum starting time, minimum supervision, minimum cost and maximum reliability. Turbines can be considered as momentum

trapping machines that converts linear motion of steam or water to rotational kinetic energy of the generator. Yadav (1972) says that the efficiency of steam turbines is about 35 to 40 %.

Bennauer et al. (2024), says that energy that is extracted from steam is expressed in terms of enthalpy drop across the prime mover also called turbine. The enthalpy drop realized across a turbine rises with rising temperature and pressure of steam and diminishes with exit pressure. The turbine operates at about 535 °C and a pressure of about 245 bars. Bennauer et al. (2024) says that modern power stations have efficiencies close to 46 %.

TURBINES



A

B

Fig 67. Pneumatic, steam or Gas turbine.

Turbines: are momentum passing and linear motion to rotational motion transfer machines that enables generation of electricity by generators. They play an in-between function between moving steam or water under pressure and the rotation of a generator.

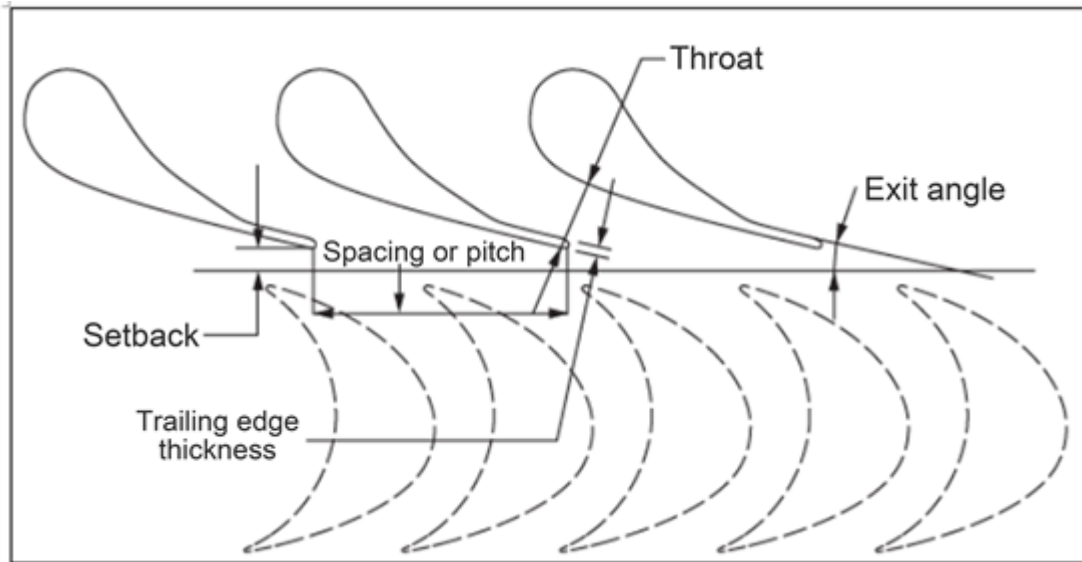


Figure 68

According to R.K. Sharma and T.K. Sharma (2010), turbines comprise of a wheel termed runner, availed with buckets or vanes along its periphery, joined to a shaft, a mechanism which regulates the amount of water/steam and passages leading from and to the wheel.

According to Coal Handling Plants report (2024), the components of a prime move or turbine are as follows: -

1. Rotor of the Turbine
2. Turbine blades
3. Turbine casing
4. Turbine nozzle
5. Journal and thrust bearing
6. Rotor coupling
7. Turning gear

The superheated steam's high velocity strikes the blades of a turbine and the steam is deflected going towards the outlet and thereby transfers the momentum to the turbine rotor or runner causing it to rotate around its shaft axis. Since the turbine

runner is connected to the generator, the generator's armature produces electricity as it rotates.

According to R.K. Singal (2009), thermoelectric power plants utilize kinetic energy of hot steam under extreme high pressure to rotate a turbine that in turn rotates the generator coupled to it to generate electrical power. In Central Receiver Tower Power plants, the heat transfer fluid which is normally a mixture of potassium nitrate and sodium nitrate is heated in the solar absorber by heat from the heliostat mirrors and pumped through a pipe to the heat exchanger. The heat exchanger heats water which expands to steam about 1 700 times change in volume. This creates huge pressure through nozzles directed to the turbine blades. The design of thermos-pneumatic pressure turbines is based on discharge available, pressure and steam velocity.

CATEGORIZATION OF TURBINES

Turbines are categorized based on 5 criteria: -

- (1) categorization based on the type of fluid that actuate or turns the turbine-generator set e.g. pneumatic turbines (gas or steam), hydraulic turbines
- (2) categorization according to hydraulic action e.g. Reaction turbines or Impulse turbines
- (3) categorization according to the direction of flow e.g. diagonal, axial, tangential or radial
- (4) categorization according to speed e.g. 1 500 rpm turbine
- (5) categorization according to the momentum or pressure that the turbine can withstand.

(a) Categorization according to pneumatic or hydraulic action

Categorization	Turbine Example
Reaction Turbines	Kaplan, Propeller, Francis and Bulb Turbines
Impulse turbines	Pelton
Deriaz	Deriaz

TABLE 11

(b) Categorization according to Direction of flow-

DIRECTION OF FLOW	TURBINE TYPE
Axial	Kaplan and Propeller
Tangential	Pelton
Mixed or Radial	Francis
Diagonal	Deriaz

TABLE 12

©Categorization according to specific speed

TURBINE TYPE	SPECIFIC SPEED(rpm)
Pelton	15-65
Francis	60-400
Kaplan	300-800
Deriaz	200-400

TABLE 13

(d)categorization based on pressure

TYPE OF TURBINE	PRESSURE/steam speed
Bulb	Very low
Kaplan	Low
Deriaz	Medium
Francis	High Pressure
Pelton	Very High Pressure

TABLE 14

Francis and Kaplan are normally designed as vertical shaft and Pelton turbines as horizontal shaft machines.

Impulse turbine

According to Kareem et al. (2018), expansion of steam through a series of nozzles directing jet of steam onto the blades of the turbine. Use upto a few megawatts.

Reaction Turbine

Kareem et al (2018), says that reaction turbines have moving and fixed blades and expansion of steam as it goes through fixed and moving blades, pressure goes down gradually across the stages. Used in large scale power stations. It can handle high pressures and high steam flow rates.

Condensing Turbine

Operates in vacuum conditions and is used in power plants.

There exist no pure impulse turbines in practice but only lower reaction turbines according to Stuck and Schurdak (2023).

TURBINE SPEED

According to Singal (2009), High speed turbines are more economical as the size of turbine, generator, power house etc. are smaller. Turbine speed must always correspond to the synchronous speed of the generator i.e.

$$N = \frac{120f}{P}$$

P

Where

P=number of poles of generator

f= frequency of the grid (60 Hetz in Zimbabwe)

Glassman (1973), highlights the 3 main steps in designing turbines as follows: -

1. Determination of speed, work and flow
2. Designing velocity diagrams in accordance to the desired number of stages and efficiency
3. Blade designs that will offer the velocities and flow angles required by the velocity diagrams. This final step comprises of determination of spacing, size and shape of the blades.

Glassman (1973) posits that velocity diagrams, inlet state conditions and flow speed determine the height of the turbine blade.

Solidity= $\frac{\text{axial code}}{\text{spacing!}}$ is considered crucial in the designing of turbine blades. A minimum value of solidity is required in order to reduce cost, cooling flow and weight of the turbine.

Mechanical considerations and increased spacing limits chord reduction results in diminished blade efficiency

Glassman (1973) says that if we assume a two dimensional flow past a passage of unit height in between two blades, the tangential force exerted by the fluid as it passes through from blade inlet to exit is: -

$$F_u = \frac{1}{g} S \rho V_{x,2} (V_{u,1} - V_{u,2}) \quad \text{Eqn 4.1}$$

Where

F_u = tangential force in N

g = conversion constant 1: 32.17 lbm/sec²

ρ = density

V_x = axial component of velocity m/sec

V_u = tangential component of velocity

Subscript 1 is for the front end of the blade and subscript 2 for the backend of the blade.

Glassman (1973) posits that the fluid exerts some tangential force as the force due to the static-pressure distribution around the blade.

The aggregate force caused by the blade by it acting on the flow along the tangential direction i.e. F_u is availed by the following: -

$$F_u = C_x \int (p_p - p_x) d\left(\frac{x}{C_x}\right) \quad \text{Eqn 4.2}$$

Where C_x = is the axial chord (m)

p_p = static pressure of pressure surface in N/m²

p_x = static pressure of suction surface in N/m²

x = axial distance measured in m

$$\text{axial solidity } \sigma_x \text{ is } \sigma_x = \frac{C_x}{s} \quad \text{Eqn 4.3}$$

Substituting Equation 4.2 and 4.1 in Equation 4.3 gives

$$\sigma_x = \frac{\rho V_{x,2} (V_{u,1} - V_{u,2})}{g (p_p - p_x) d(x/c_x)}$$

$$\psi = \int_0^1 \frac{(p_p - p_x) d\left(\frac{x}{C_x}\right)}{p_1 - p_2}$$

where

p_1 =inlet total pressure N/m^2

ψ =Zweifel loading coefficient

p_2 = exit static pressure N/m^2

Glassman (1973) posits that the components of which the velocity is comprised of in terms of flow angle and velocity are expressed as: -

$$V_u = V \sin \alpha$$

$$V_x = V \cos \alpha$$

Where

V = velocity of fluid m/sec

α =flow angle of fluid (in degrees)

ROTOR OF A STEAM TURBINE: PHOTO BY iStock Photosoup



Figure 69



Figure 70

According to Coal Handling Plants report (2024), the modes of startup of steam turbines are as follows: -

- cold start up-shut down time greater than 72 hours
- warm start up- shut down time between 10 hours and 72 hours
- Hot start up-shutdown time less than 10 hours.

Advantages of Steam Turbine According to Balaji et al (2016) are as follows: -

- a prime mover could generate greater speeds and a higher range is practical,
- higher efficiency
- less steam consumption,
- the turbine is comparatively safe since all moving parts are closed in a casing,
- since there is little vibration lighter foundation and less space is required,
- few sliding parts results in less frictional losses,
- more uniform applied torque to the driven shaft in the steam prime mover,
- requires little attention during running and therefore less repair costs.

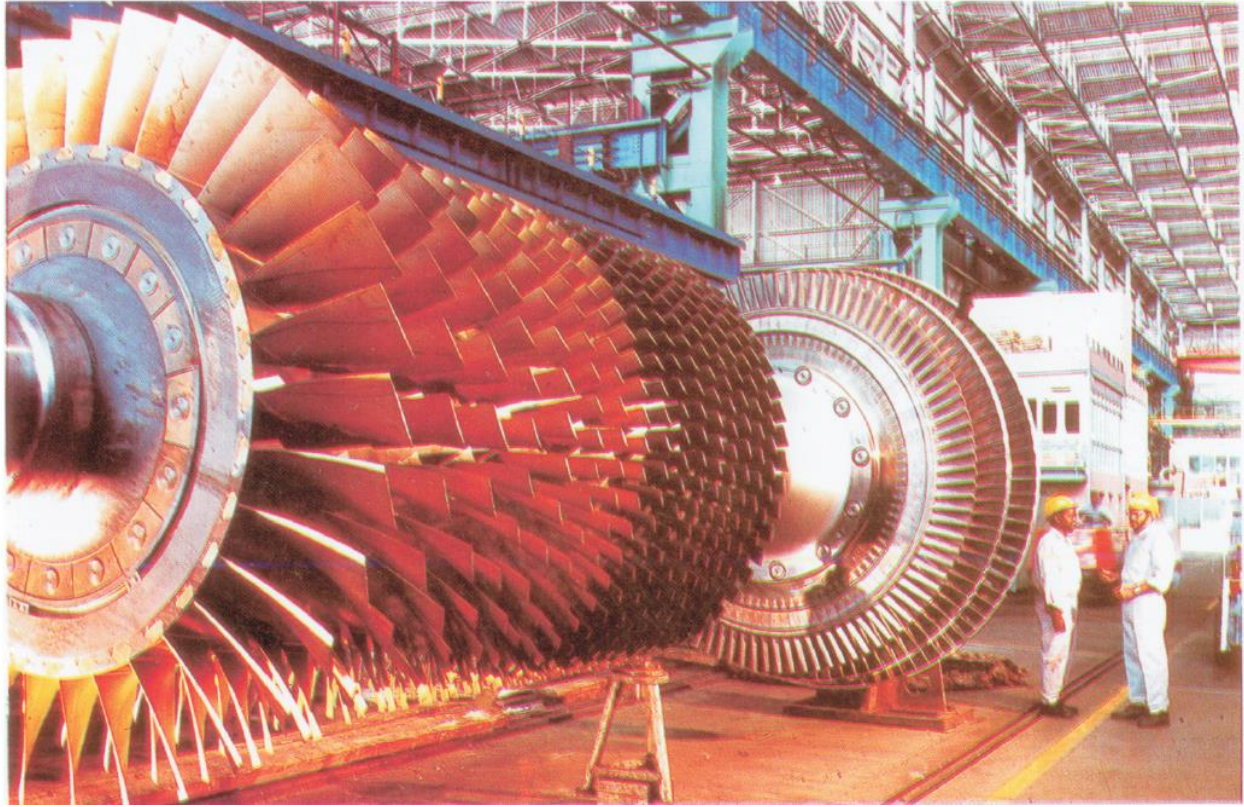


Figure 71

TURBINE DESIGN

According to Balaji et al. (2016), blades can be made from austenitic alloys, titanium alloy, plastic reinforced carbon or 304 stainless steel. Nickel chromium alloys and aluminum and vanadium alloys may also be used.

According to Stuck and Schurdak (2023), the stresses created in the blade are caused by centrifugal forces, steam temperature and steam pressure caused by movements of rotation. The better the blade design, the more efficient the turbine is going to be and the more efficient the generator.

The temperature and pressure of each stage determines the kinds of materials for the blades. The High Pressure(HP) stage, the Intermediate Pressure(IP) and Low Pressure(LP) stage produces different kinds of stresses and forces to the blades. Stuck and Schurdak (2023), says that Lower density enables lengthening of LP blades and therefore enhance efficiency of turbine without enhancing or up-scaling

stress. The lengthened blades in the LP stage have more centrifugal forces. There are higher levels of moisture in the LP stage and titanium alloys with higher corrosion resistance than steel become the best materials for the LP stage.

Steam turbines of fossil power plants normally operate at 3000 -3600 rpm.

There are static and dynamic forces on the blade. The static forces include centrifugal tensile stresses and centrifugal bending loads. Dynamic forces on blades are caused blade vibrations caused by non-uniform steam flows and resonance of the blade's natural frequency with blade vibration.

According to Stuck and Schurdak (2023), blades in LP stages are longer than blades in HP and IP. Centrifugal forces in HP and IP are less than in LP stage due to blade lengths which are longer in LP. As steam heats blade, it causes steam bending forces. Bending due to steam are about 10 % of centrifugal stresses according to Stuck and Schurdak (2023).

Steam bending is greatest in HP due to high pressure of steam, but also occurs at a reduced level in IP and LP. Steam bending is also substantial in LP because of longer blades. Blade vibrations causes dynamic forces. Resonance which occurs when natural frequency of blade is same as frequency of vibration, can be dangerous.

All the stresses above propagate cracks and dislocations in turbine blade material. The cracks and dislocations lead to blade corrosion in the cracks. More mainly corrosion occurs in LP due to lower temperatures. Corrosion reacts with blade material.

Technical Data for the BHEL 500 MW Steam Turbine according to Yahya (2011)

[1]Rating	500 MW
Rated speed	3000 rpm
Temperature of steam at inlet	537°C
Pressure of steam at inlet	166.716 bar (170 kgf/cm ²)
Steam flow rate	1500 tonnes/hr.
Type	Reaction
Number of cylinders	Three
High pressure	1
Intermediate pressure	1 (double flow)
Low pressure	1 (double flow)
Number of stages:	
High pressure	17
Intermediate pressure	2 × 12
Low pressure	2 × 6
Mean diameter (first stage)	1792 mm
Mean blade ring diameter (last row)	3650 mm
Height of the last blade row	1050 mm
Reheat steam temperature	537°C
(between H.P. and I.P. cylinders)	
Condenser pressure	0.1013 bar (0.1033 kgf/cm ²)
Mode of governing	Throttle (Electro Hydraulic)

TABLE 15

GENERATOR DESIGN

$$N = \underline{120f}$$

P

Where f=grid frequency (60 Hetz in Zimbabwe)

P=number of poles of generator

Grid frequency=60 Hertz

N=3 000 rpm

From $N = \frac{120f}{p}$

$$p = \frac{120 \times 60}{3000} = 2.4 \text{ Pole}$$

The number of poles cannot be odd e.g. 3 since they exist in pairs, therefore the generator will have 4 poles to the nearest

From $N = \frac{120f}{p}$, if frequency is =60 Hz, $N = \frac{120 \times 60}{4} = 1\,800$ rpm instead of 3000 rpm.

This means the flow of steam or steam velocity will have to be reduced to slightly more than half

If the number of pole pairs is taken to be 2, N=3 600 rpm which means the velocity of steam to turbines has to be slightly increased.

If the frequency of the grid is 50 Hz and we are outputting 60 Hz, we can use a frequency converter to change the frequency from 60 Hz to 50 Hz.

According to Toppr(2024), the specific heat capacity of steam= 1 996 J/kg K. The temperature of steam =565 °C and average room temperature =20 °C, therefore temperature change =

$$(565-20) = 545 \text{ }^{\circ}\text{C}.$$

Energy transferred to steam=mcΘ= 500 MW

WHERE m =mass of steam heating the turbine blades per second, c =specific heat capacity of steam and Θ =temperature rise of steam

$$m \times 1996 \times 545 = 500 \text{ MW} = 500\,000\,000 \text{ W}$$

$$m = 459.634 \text{ kg approximately} = 460 \text{ kg per second}$$

$$\text{kinetic energy of moving steam} = \text{power station output plus losses} = 500 \text{ MW} = 500\,000\,000 \text{ W}$$

$$\frac{1}{2}mv^2 = 500\,000\,000 \text{ W}$$

$$\frac{1}{2} \times 460\,000v^2 = 500\,000\,000$$

$$230v^2 = 500\,000\,000$$

$$V^2 = 2\,173\,913 = \text{approximately} = 2\,200\,000$$

$$V = 1,490 \text{ m/s should be the velocity of steam hitting the turbine blades}$$

$$V = \text{approximately } 1.5 \text{ m per second}$$

According to Toppr (2024), the density of steam at $1 \times 10^5 \text{ Pa}$ is 0.6 kg/m^3

$$0.6 \text{ kg} = 1 \text{ m}^3$$

$$460 = ?$$

Simple proportion

$$460 \times 1 / 0.6 = 767 \text{ m}^3$$

$$\text{Mass} = \text{density} \times \text{volume}$$

$$460 \text{ kg} = 0.6 \times \text{volume}$$

$$\text{Volume} = 767 \text{ m}^3$$

$$\text{Area of turbine blades} = \text{volume} / \text{velocity}$$

$$\frac{767}{1,490} = 514.7 \text{ m}^2 \text{ is the total area of blades to be hit per second by steam.}$$

Assuming 20 rows of blades, the area that must be struck per row= $515/20=25.75\text{m}^2$

Total Area in each row of blades= 26 m^2

Assuming about 5 blades on each row are exposed to steam momentum, area of each blade= 5.2 m^2 . Assuming each blade is a square, each side = 2.28m . If each blade is a rectangle of width 1 m , then each blade's length= 2.28m . Allowing centre radius of turbine blade holding drum to be 0.3 , total radius of turbine blades= 2.58m , approximately 3m . The diameter of the turbine blade circle= 6m being the length from the tip of a blade to the tip of the blade directly opposite it on the drum.

BLADE DESIGN (According to Stuck and Schurdak (2023))

1. the material for the blade must possess sufficient yield strength that resist plastic deformation at raised temperatures,
2. the material must be able to be worked on easily, this is the downside of titanium which cannot be worked on easily,
3. blade materials should have moderate elastic modulus in order that the blade does not deform excessively and not break suddenly under stress
4. blade materials should have low density to reduce centrifugal forces, centrifugal stresses transmitted to the blade
5. material must be corrosive resistant,
6. blades should not crack easily

Aerodynamic shape increases efficiency. Blades greatly impact on overall turbine efficiency.

A 500 MW Central Tower power plant needs a 500 MW generator and a 500 MW turbine which are recommended for this project. A 120 MW turbine and a 120 MW generator are required for integrating with Munyati power station.

The project now proceeds to the design of tubes, electric pumps and valves

3.10 DESIGN OF THE ELECTRIC MOTOR, PUMP & TUBING FOR THE 500 MW CENTRAL RECEIVER TOWER POWER PLANT

INTRODUCTION

The tubing, electric pumps and valves form the thermal energy storage fluid and working fluid circulation systems whilst the fluids (molten salt and water) form the bloodstream of the Central Receiver Tower Power Plant. Tubes are the conduits for conveying molten salt from Cold Thermal Energy storage tanks to the receiver, from the receiver to the Hot Thermal Energy storage tanks and for conveying molten salt to the condenser and back to Cold Thermal Energy Storage Tanks and water from the borehole to the cooling tower to the condenser to the heat exchanger and back to the cooling tower. Tubes can be considered solids i.e. metal, hard plastic, wooden objects or entities which are continuous for a given length with a hole inside to guide, direct, channel or constrain a fluid in order for the fluid to flow in a given direction without leaks to the external of the tube. The pumps form the heart of the above system whilst the valves are for control, regulation and directing of the flow of the molten salt and water within the tubes or pipes. The electric pumps regulate the speed of flow of the fluid within pipes This paper is for sizing, dimensioning and selection of materials for the tubes, electric pumps and the valves. The valves may be operated manually or electronically through an electrical and electronic control system. Valves can also be bi-directional or non-return valves.



*

Figure 72



Figure 73 :ELECTRIC PUMP

MAIN NARRATIVE

The thermal storage fluid (i.e. molten salt which is a mixture of potassium nitrate and sodium nitrate in the ratio 3:2) carries heat from the receiver to the energy storage tank or heat exchanger. It is also moved through pipes from the heat exchanger to the cold thermal storage tanks. The purpose of the working fluid which is water is to assimilate heat and provide pressure when it changes state from liquid to gas i.e. water vapor when its volume changes in the ratio 1:1 600 times. Water is obtained from a borehole or any water source, then circulated in the cooling tower to get some heat and then goes to the heat exchanger. It then goes to the condenser then cooling tower.

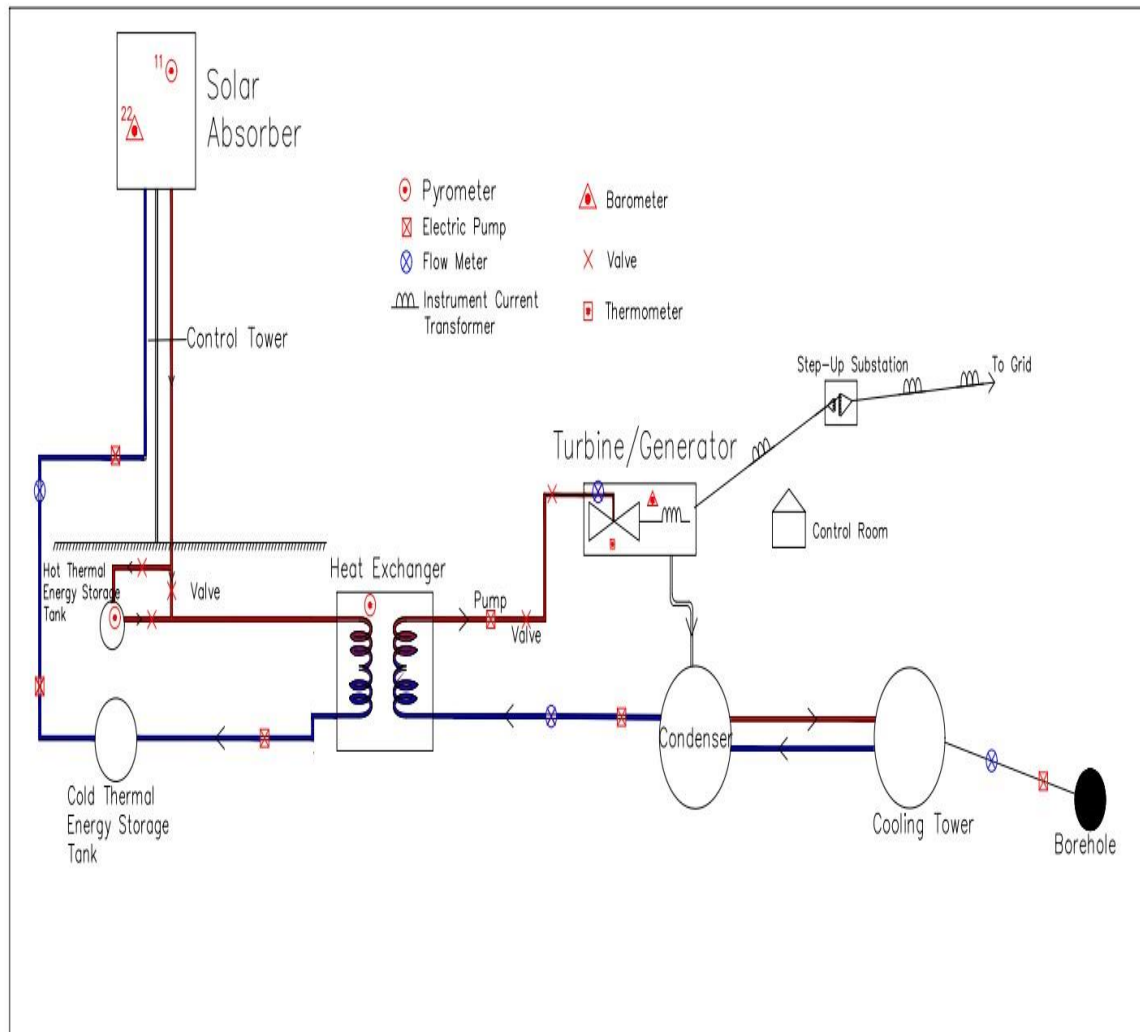


Figure 74

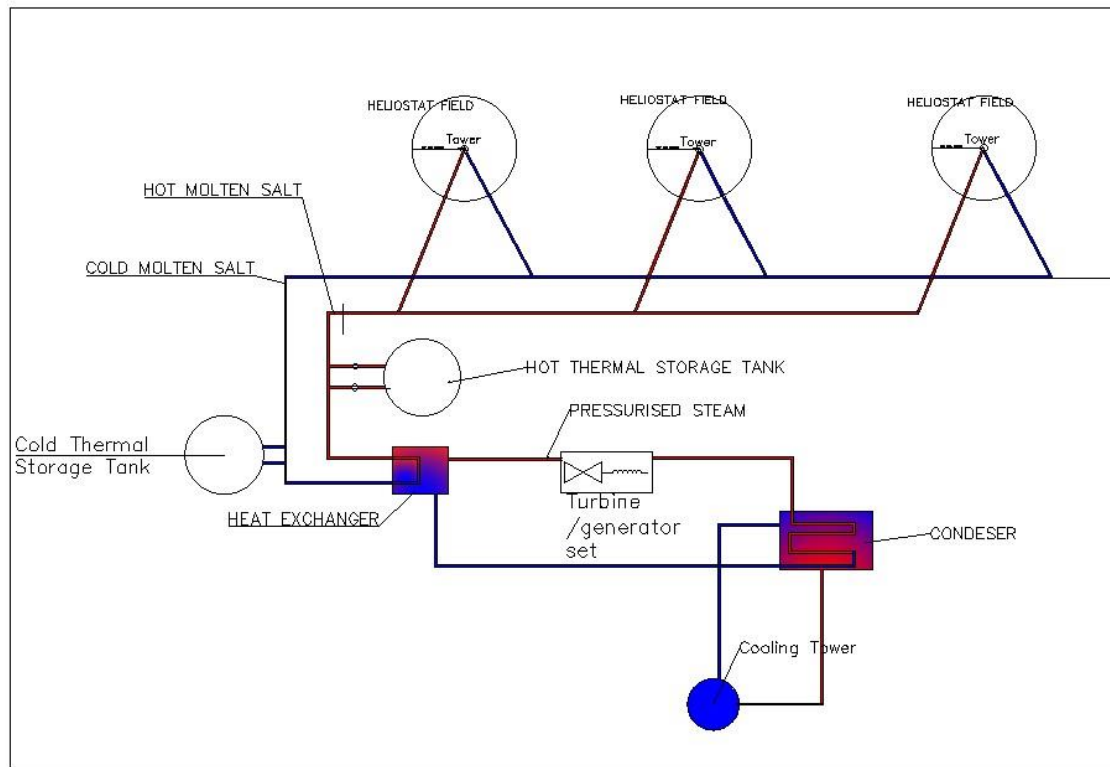


Figure 75

Tubing

According to GlobalSpec (2025), tubes are hollow cylinders utilized for transporting fluids from one place to another. Tubes may have square, rectangular or round cross section. Tubes and Pipes are normally interchangeable names.

Tubes can be classified according to the material they are made from. E.g. metal or plastic tubes. In our case we will not be talking of plastic tubes because of high temperatures involved in Concentrated Solar Thermal Power Plants.

Aluminum Tubes

Aluminum is corrosive resistant and has light weight characteristics. It has low tensile strength and is usually alloyed with zinc, copper, silicon and manganese to improve its strength.

Copper Tubes

It has good conductivity and is corrosive resistant. We will use them in the heat exchanger, cooling tower and condenser.

Steel tubes

Steel is corrosive resistant.



Figure 76

The tubes will need to be insulated using Mica wool (upto 1 000 °C) or Ceramic fiber (upto 1 430 °C). Putting insulation on the outside of tubes prevents heat losses and enhances power plant efficiency.

The Electric Pump

According to Waqar (2025), an electric pump is a gadget that employs electric energy to propel or push fluids (i.e. molten salt or water) within tubes. The electric motor drives this pump. The pump and the electric motor unit is collectively called the electric pump. An electric pump transforms or converts electricity into mechanical hydraulic power resulting in a fluid acquiring and possessing kinetic energy within tubes.

In our thesis we want to employ electric pumps to drive molten salt up and down the tower, from tower to Hot Thermal energy storage tanks or heat exchanger, from condenser to cold thermal energy storage tank and water from water reservoir (e.g. borehole) to Cooling tower to condenser to cooling tower.

Waqar (2025) says that submersible pumps are multi-stage centrifugal pumps that do work in a perpendicular position. While the given shaft of the submersible pump is rotating, the impeller rotates also forcing the fluid to the bottom via the inlet of the pump. The submersible pump pushes rather than pull the fluids. The impeller throws water outwards and forwards. Waqar (2025) says that the submersible electric pump is very economic and effective in lifting or pushing huge volumes of fluids. It can run for several years (Waqar, 2025).

COMPONENTS OF AN ELECTRIC PUMP

- Motor
- Casing
- Protector
- Pump
- Inlets
- Power cables

MOTOR

Submersible pump which uses electricity has a 2-pole, 3 phase squirrel cage induction motor that works at 60 Hertz with a speed of 3 500 rpm (Waqar, 2025).

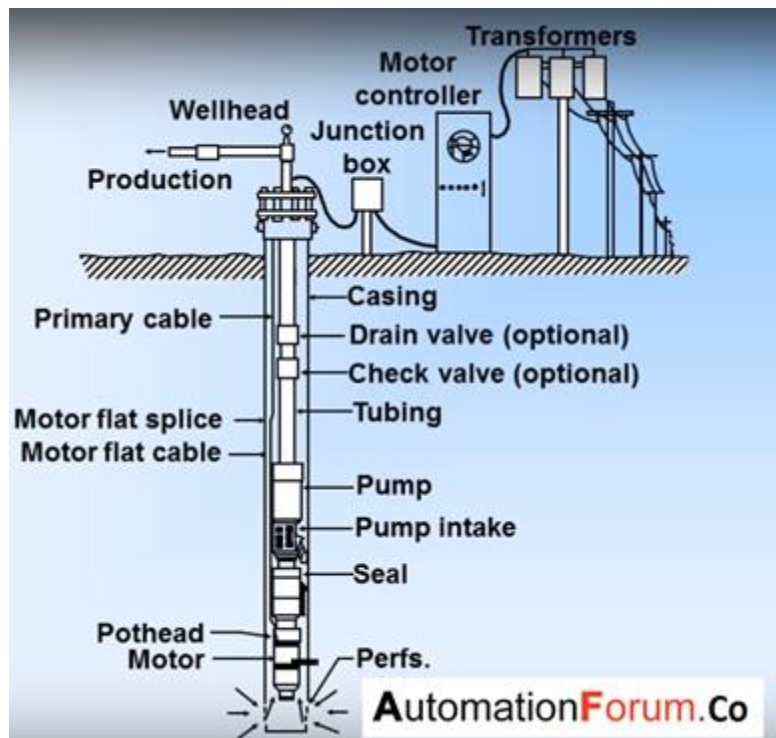


Figure 77

According to Ashlin (2019), a pump is employed to transfer or make a fluid move from source (original position) to destination or ensure circulation of fluids around tubing systems.

Types of Pumps

1. Direct lift pumps
2. Displacement pumps and
3. Gravity pumps.

An electric submersible pump is a subsurface centrifugal pump with multi-stage driven by an electric motor (Ashlin, 2019). The rotating impeller spins and pushes the fluid towards the desired direction.

VALVES

Valves stop or allow flow of fluid in tubes. They control, regulate or direct the flow of molten salt or water in our project.

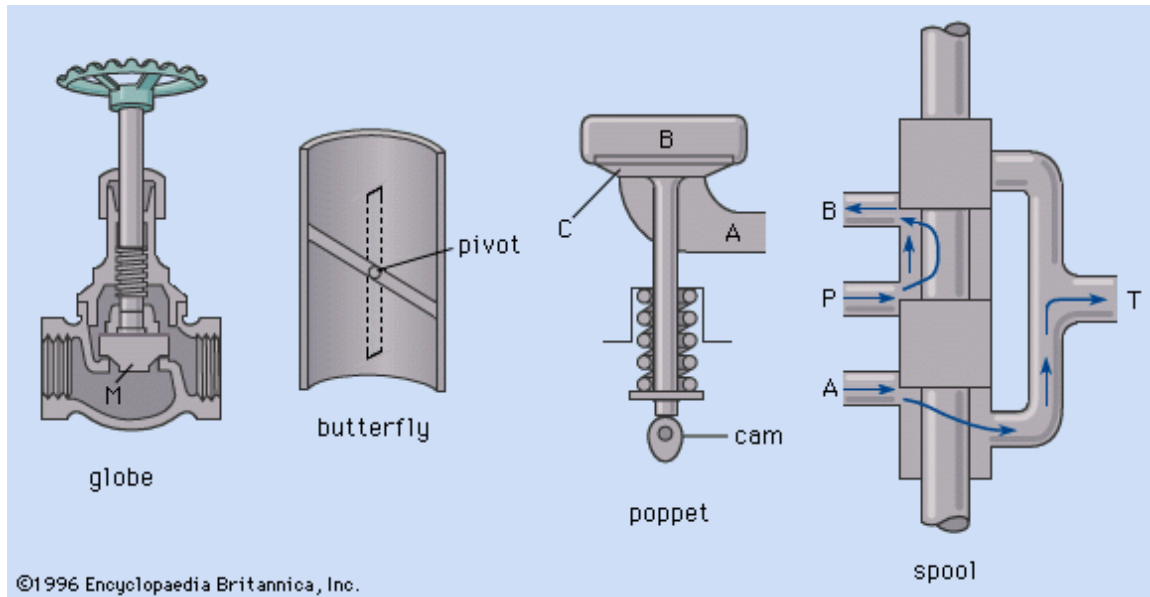


Figure 78



Figure 79

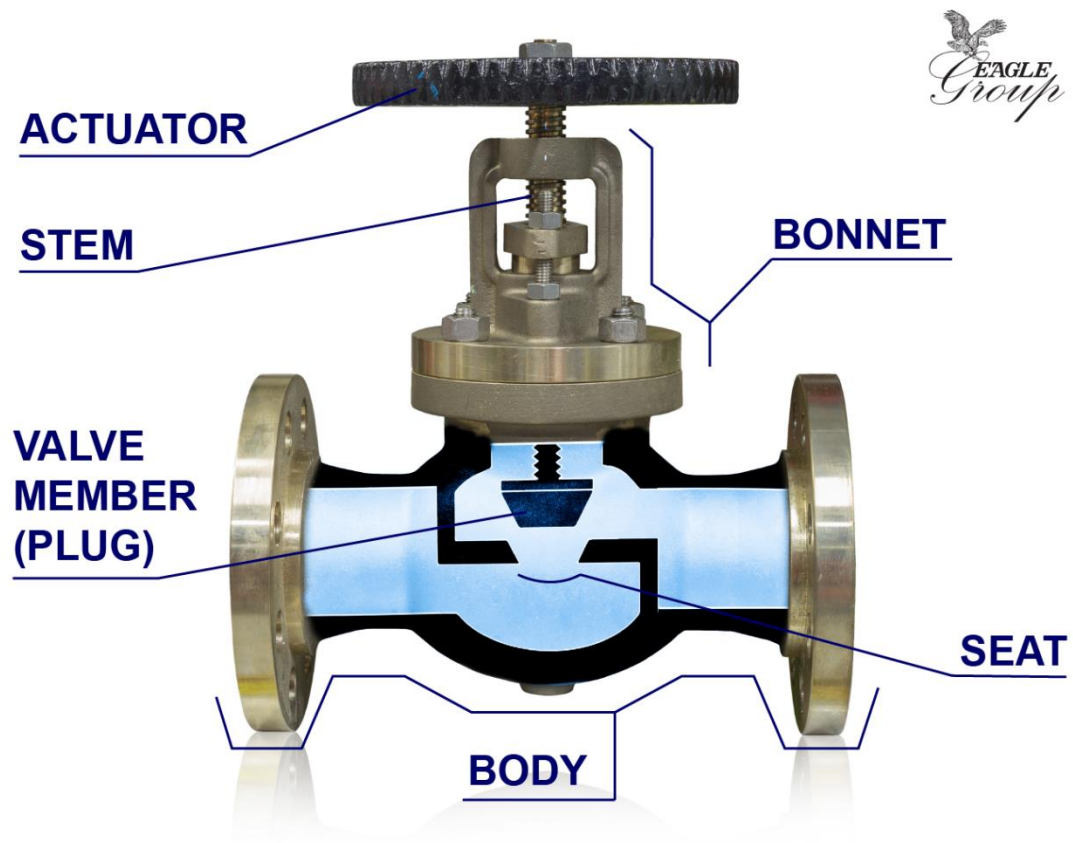


Figure 80

WHAT IS A VALVE?

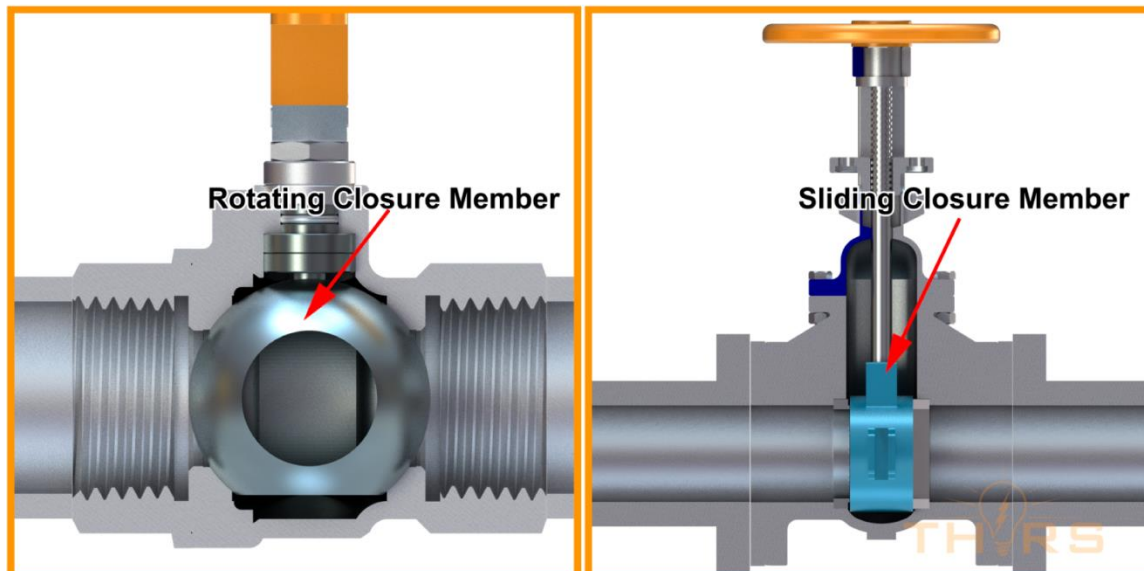


Figure 81

We are designing a 240m high tubing of 0.02m radius for a tower. If the receiver is assumed to be 10m high. The total height of the fluid from ground=250

This means the volume of one tube up the tower $=(\pi r^2 h) \text{ m}^3 = \pi (0.02)^2 \times 250 = 0.31429 \text{ m}^3$.

Density of a mixture of sodium nitrate mixed with potassium nitrate in the ratio 2:3=2.17g/cm³.

Mass=Volume x Density=314290 x 2.17g=682 009.3 g=683kg

Downward force=mg=683 x 9.81=6 700.23= 6 700. 230 N=6.7 Kn

The 6.7 Kn need to be moved by 20m per second= 134 KW

Approximately 150 Kw motor and pump will be required.

Volume (V) of 250 molten salt column in a pipe of radius 0.02 m $=\pi r^2 h = (22/7) \times (0.02)^2 \times 250 = 0.3143 \text{ m}^3$

Mass of molten salt column in tube = Volume x Density

$$= 0.3143 \times 2170$$

$$= 682 \text{ kg}$$

Force in Newton =mg=682 x 9.81=6 691 N=6.891kN

The above force need to be applied for 240m high

We first attempt to find the mass of molten salt contained in pipe or radius 0.02m, given specific heat capacity of the mixture of potassium nitrate and sodium nitrate in the ratio 3:2 and Θ to give 500 MW.

$mc\Theta=500 \text{ MW}$, Where $m=\text{Volume} \times \text{Density}=(\pi r^2 h \times 2170)$

$c(\text{potassium nitrate})=1118 \text{ J/kg/K}$

$C(\text{sodium nitrate})=1094 \text{ J/kg/K}$

In ratio 3:2 $c=1108 \text{ J/kg/K}$

$\Theta=(565-20)=545$

$M=500000/(1108 \times 545)=0.828 \text{ kg per second to give 500 MW}$

$\pi r^2 h \times \text{density}=\text{mass}=0.828$

$h=0.828/(\pi r^2 \times \text{density})=0.3035 \text{ m}=303.5 \text{ mm per second}$

from previous calculations the mass of molten salt in the power up the tower and receiver=682kg

$\text{Kinetic energy}=(1/2)mv^2=(1/2) \times 682 \times (0.828)^2$
 $=233.78 \text{ J per second}$

$\text{Kinetic energy per m second}=233.78/0.3035=770 \text{ Watts}$

Therefore, the size of electric pump required for the 500 MW **Central Receiver Tower Power Plant=770 Watts**

VALVES

Non-return valves need to be installed (1) just before pipe up the tower (2) just before cold thermal storage tank (3) just after the condenser (4) just after the cooling tower (5) just after the heat exchanger (6) Just before the Hot thermal energy storage tank from receiver and (7) just after hot thermal energy storage tank to heat exchanger.

A float switch need to be installed on top of molten salt in the receiver controlling the valve from cold storage tank to receiver to prevent over supply of molten salt to receiver.

The project now proceeds to design a step-up substation

3.11 Design of a 500 MVA, 30/132/330 Kv Step-up Substation for a Central Receiver Tower(CRT) type power plant for Kadoma District in Zimbabwe

INTRODUCTION

This section posits that the output of Central Receiver Tower (CRT) power plant in question will be at 30 kv. This voltage needs to be stepped up to 132 Kv for transmission to bulky supply points in Kadoma in order to minimize transmission losses(I^2R). When one steps up the voltage, the current goes down so that the power at the primary is the same as that at the secondary of the transformers.

This section is a technical paper on the design of such a substation. It highlights that soil resistivity tests for the site needs to be carried out in order to design the Earthgrid of the substation. All metal work except the actual conductors carrying current need to be connected by copper conductors to the earth grid 1.5 m deep into the ground including the overhead catenary wire. The transformer tanks, the breaker tanks and the isolator operating handles have to be connected to the earth grid by copper wires of sufficient cross sectional area. This will ensure safe touch and step potentials within the substation.

The boundary of the substation has to be 100m by 70m and fenced or durawalled. The transformer pads have to be 3mx2m by 3m deep. Breaker pads have to be 2m x2m by 3m deep. Isolator pads have to be 2m x 2m by 2m deep

The section describes substations as a geographical arrangement of components and equipment such as power transformers, breakers, isolators, jumpers, lightning arrestors, instrument voltage and current transformers, earth-grid and earth marts, catenary wires etc for the purpose of changing one voltage level(incoming) to another which is different(outgoing) and dispatch power to an electrical network or grid.

MAIN NARRATIVE

There are two types of substations namely (a) step-up substations where the voltage is being raised from a lower level (generation voltage) to a higher level (transmission voltage) and step-down substations where the voltage is being scaled down from a higher voltage (transmission voltage) to a lower level voltage (e.g. distribution voltage). In this project we are designing a step-up substation.

A typical substation has the following

- Transformers for voltage transformations and adjustments. Transformers are the heart of a substation.
- Circuit-breakers for current breaking and contacts making for current flow facilitation and prohibition. There is an a.c. auxiliary supply circuit connection between relays and breakers., a d.c. supply circuit between d.c. batteries and relays.
- Isolators for equipment isolation. Isolators are normally connected on both sides of transformers and breakers.
- Busbars
- Protection relays for detecting faults and sending trip signals to breaker closing motor
- Condition-monitoring equipment
- Instrument voltage transformers and instrument current transformers for scaling down of power signals to levels suitable for measurement and acceptable to relays! Instrument transformers are also used for Metering as well as for protection
- Earth grid and earth-mats for connection to all metalwork except the conductors meant for carrying load current
- Communication equipment
- Lightning arrestors and arcing horns for overvoltage protection. Over-voltages are caused by lightning strikes and switching. Surge arrestors are normally installed on both sides of power transformers and near incoming lines.
- Jumpers
- Space and room for driveways
- Control building
- D.C. Batteries and d.c. circuits
- Auxiliary a.c. power circuits e.g. breaker motors
- SCADA software

- Pads for transformers, breakers and isolators
- Catenary wires and or earth mast above the substation connected to the earth-grid on several points for shielding the substation's equipment from lightning strike.
- Substation fence or durawall to prevent unauthorized access, sabotage or vandalism.
- Substation surveillance equipment and intrusion detection including CCTV cameras.

There is need for clearances between conductors and buses from each other as well as from each conductor or bus to earth or ground. According to EEP Academy (2024), if line to earth or double line to earth fault happens, we must prevent dangerous touch and step potential voltages on the substation ground and equipment casing e.g. transformer tanks and ground for safety to personnel.

Instrument Current and Voltage Transformers

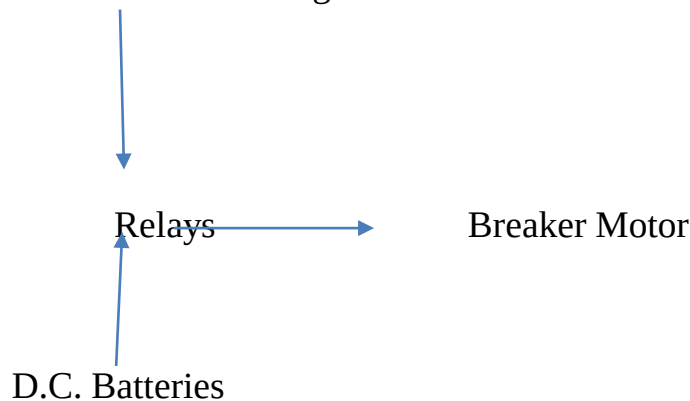


Figure 82

There is need for equipment sizing and dimensioning. Voltage and current ratings for transformers, breakers and isolators need to be ascertained. Voltage withstand limits for the transformers and breakers need to be known and confirmed in the design.

The steps for substation Construction are as follows: -

1. Feasibility studies
2. Site selection
3. Conceptual design

4. Detailed engineering designs (structural, civil and electrical engineering drawings)
5. Regulatory approvals
6. Land acquisition
7. Stakeholder coordination and construction
8. Tests and commissioning
9. Synchronization and grid-connection

Clearances which depends on voltage levels, break-down strength of air or humid air plus safety margins have to be allowed for in equipment spacing in the substation. Safety to personnel and equipment dictates substation design methodology.

The site plan details equipment layout and a vertical aerial view of the substation together with its components. Civil-structural designs and drawings for the control building, pads and Earthgrid needs to be given attention. Electrical single line diagrams, protection schematics and wiring diagrams need to be drawn by a qualified electrical engineer.

Step-up substations like the one being designed raise generation output voltage to suit needed higher transmission level voltages.

According to Padilla (2016), the prime aim in the operation of an electrical power system is the energy balance between generation and demand economically. A power system consists of power stations, feeders, substations and distributors. Within this power system, it is imperative that voltages and frequencies are kept within acceptable specified range limits (Padilla (2016)). The rotational speed of generators determines the system frequency whilst, the tap changers on transformers control voltages within feeders and distributors.

There are mainly two types of substations namely step-up substations and step-down substations. Substations may also be classified as (1) transmission substations (2) sub-transmission substations and (3) Distribution substations. Substations change incoming voltages(V) and currents(I) to different values or levels on the outgoing side while maintaining the power (VI) level constant. If voltage is stepped up, the current is stepped down. If voltage is stepped down, the current is stepped up. We only consider the voltage when classifying substations as step-up or step-down substations.

Rao (1992) says that an electrical network consists of the following: -

- Generating substation- step up substations which we want to design in this project
- Transmission system
- Receiving substations (step down substations-transmission and sub-transmission substations)
- Distribution substations
- Distribution network
- Load points

According to Rao (1992) substations can be classified according to (1) voltage levels (2) outdoor or indoor (3) configuration e.g SF6 gas air insulated S/S or oil insulated substation and (4) application e.g. switching substation, sending end substation, receiving substation or distribution substation.

FUNCTIONS OF A SUBSTATION (According to Rao (1992))

1. To supply electrical power within specified voltage limits.
2. To supply electrical power within targeted frequency
3. Electrical Signal conditioning (matching voltages on the incoming and outgoing sides on either sides of the substation as required by the electricity grid) on-load and off-load tap-changing may be required to give the required quality of supply

According to Rao (1992), a substation normally has 2 or 3 voltage levels. A substation layout is the physical arrangement of various components in the substation relative to each other and boundary fence (Rao (1992)). Substation layouts have significant influence on the protection, maintenance, cost and operations and therefore these activities and considerations dictate substation layouts (Rao (1992)). Normally a substation has incoming lines called 'incomers' and outgoing lines.

Essential Features of a Typical Substation (According to Rao (1992))

- Outdoor switchyard
- Roads and rail track for transporting equipment
- Incoming line towers and outgoing line towers cables

- Overhead shielding
- Substation lighting system
- Fence and gate
- Office building
- Civil works
- D.C. battery system and d.c. LV distribution system
- L.V. and M.V. system for auxiliaries
- Substation stones

Equipment Layout

- Equipment positioning
- Arrangement of bus-bars
- Auxiliary M.V. a.c. electrical power networks
- D.C. circuits from batteries to relays
- Layout of Control Building
- Earthing and over-voltage protection

Relay Protection and SCADA

- INSTRUMENT equipment e.g. VTs and CTs
- Metering
- Remote control and communication equipment

Needed Drawings

- Architectural Drawings for Control Building
- Structural and civil Engineering Drawings for Control Building
- Electrical single line diagrams
- Electrical protection schematics
- Electrical wiring diagrams
- Structural drawings for pads, foundations and earth-marts

EQUIPMENT IN A TYPICAL SUBSTATION

1. Power Transformers
2. Breakers
3. Isolators
4. Instrument Current transformers
5. Instrument voltage transformers
6. Lightning arrestors
7. Arcing horns
8. Catenary wire
9. Relays
- 10.D.C. battery banks
- 11.Control room
- 12.Bus-bars
- 13.Transformer pads, breaker pads and isolator pads
- 14.Earth grid
- 15.Auxiliary power transformer
- 16.jumpers

POWER TRANSFORMERS

These are the part of the electrical system for conveying power from generating stations to load centres whilst stepping up or stepping down the voltage while power remains constant. Standard power transformers are in the Zimbabwe Electricity Supply Authority (ZESA) are 11/330 kv, 33/330, 11/132, 30/132, 30/330, 330/132, 132/33, 330/88 kv. In terms of MVA rating standard sizes are 1 MVA, 3MVA, 5MVA, 7.5 MVA, 10 MVA, 15 MVA, 20 MVA, 50 MVA, 75 MVA, 100 MVA, 200 MVA and 250 MVA and 500 MVA. In this design 2 of 250 MVA 30/132 kV power transformers will be used.

According to Rao (1992) for up to 11 kV are either brick-built indoor metal clad draw-out type switchgear or outdoor fibre glass kiosk type. For voltages of 33 kV and above, outdoor substations are generally preferred. The proposed power station outputs 30 KV which must be transformed to 132 kV and two 250 MVA.

According to Transend (2024), the following details for power transformers are necessary: -

- Cooling class
- Voltage ratios

- Frequency
- Power rating and overload capacity
- Basic Insulation Level (BIL) for low and high voltage sides
- Impedance of transformer
- Sound level
- Tap changing –no-load and load tap changing

Assuming One Transformer

Voltage ratio=30/330 KV

For a 500 MW power station, assuming a power factor of 0.9 =556 MVA

If rated voltage at the primary=30 Kv, Rated Current = $\frac{556}{30}=18.5$ kA

At the secondary 330 kv, Rated Current= $\frac{556}{330}=1.68$ kA

Frequency=50 Hertz which is standard in Zimbabwe

Power rating of Transformers = 2 x 250 MVA

Tap changing=on-load tap changing

Assuming Two Transformers of 250 MVA

Rated Power=250 MVA=225 MW assuming a power factor of 0.9

Primary voltage =30 Kv

Rated Primary Current== $\frac{250}{30}=8.33$ kA

Secondary Current= $\frac{250}{330}=0.76$ kA

Rated Frequency=50 Hertz which is standard in ZESA

Tap Changing= Load tap changing

CIRCUIT BREAKER RATINGS

- Maximum rated voltage (30 kV primary AND 330 kV secondary)
- Basic Insulation Level (BIL)
- Rated continuous current (8.33kA primary and 0.76 kA Secondary)
- Short circuit current which is rated
- Interrupting time
- Rated frequency (50 hearts which is ZESA standard frequency)

INSTRUMENT CURRENT TRANSFORMER RATINGS

- Rated Frequency
- Rated Current
- Basic Insulation Level
- Transformation ratio
- Accuracy class

Instrument Voltage Transformer Ratings

- Rated primary voltage=30 kV
- Rated voltage ratios (30/0.012) =30 000:12 primary and 330 000:12 secondary
- Rated voltage factor
- Accuracy class
- Rated secondary voltage (330 kV)
- Rated thermal limiting output
- Voltage ratio error

ISOLATOR SWITCH RATING

- Rated Current
- Rated frequency
- Rated voltage
- Peak withstand current
- Lightning Impulse withstand

Breakers

The purpose of breakers are as first points of breaking or making electrical circuits i.e. making electrical circuits discontinuous or continuous. The contacts are insulated in a steel chamber with SF₆ gas or oil as arc quenching medium. Breakers are first operated before operating isolators. The breakers must be able to break a load of 250 MVA/30 KVA=8.34 kA approximately 9 000A on the primary and 250 MVA/132 KV=1.894=1.90 Ka approximately 2kA OR 2 000 A on the secondary.

ISOLATORS

The function of isolators is to isolate equipment such as transformers and breakers from energized parts or any source of supply before working on the equipment which must be earthed on either side. It is forbidden to make or break circuits with isolators which do not have arc quenching medium such as SF₆ or oil. Isolators do not have arc quenching medium such as SF₆ or oil.

Instrument Current Transformers

The purpose of instrument transformers is for measurement of current in the incoming and outgoing circuit from the transformer or feeder. From calculations under power transformers, 9000/5 Current transformers on the primary side and 2000/5 current transformers on the secondary side need to be used. Both Current Transformers will output a maximum of 5 A for relay operation

VOLTAGE TRANSFORMERS

The power station outputs 30 KV which needs to be transformed to a maximum of 10 V. The instrument voltage transformer's turns ratio on the primary side =30 000/10=3 000:1. The turns ratio on the secondary side =132 000/10= 13 200:1.

LIGHTNING ARRESTORS

The purposes of lightning arrestors and arcing horns on transformers and feeders is for over-voltage protection. They conduct current to the earth grid if there is an overvoltage caused by switching surges or lightning which exceeds set-current. On the primary side the arcing horns and surge arrestors should operate if the current exceeds 9 000 A on the primary and 2 000 A on the secondary. These values are taken from calculations on current transformers.

CATENERY WIRE

These are copper wires which are strung on top of the substation from corner to corner for shielding and lightning protection of the equipment such as transformers and breakers.

RELAYS

There are electro-mechanical and electronic relays and for this design electronic relays which are modern are recommended. According to Padilla (2016) Relays are devices that accept inputs and process them using logical algorithms to develop outputs addressed to make decisions resulting in alarm signals or trip commands. Relays normally get inputs from sensors such as instrument current transformers and instrument voltage transformers and output signals to trip coils of breakers or alarm LEDs on the relay. Relays are controllers which regulate breakers if there is an over-voltage, over-current or an earth fault. They are housed in the control room. They get signals to trip from instrument voltage transformers and instrument current transformers. Relays have got 2 settings namely alarm and trip. Relays have normally open and normally closed contacts. The normally open contacts close if there is an over-voltage or over-current or earth fault.

INTEGRATED DIGITAL UNITS(IDUs)

These are also called multifunctional relays and perform several functions such as monitoring, protection, control and communication (Padilla (2016). This kind of device is widely deployed in particular for medium voltage substations where required availability is not a critical aspect according to Padilla (2016).

D.C. Battery Bank

These are for activating control contacts circuits in relays which also supply breaker trip contacts. They are normally 12 V battery banks.

CONTROL BUILDING

This is a building housing relays, battery banks, and an office for local control of the substation variables. Breakers can be opened or closed in the control room or in the switch yard or from the National Control Centre.

Busbars

These are for tying together incoming lines or outgoing feeders from the power transformers.

Transformer pads

These are concrete platforms on which the power transformers sit. The transformer tank is connected to the earth grid via a copper bar for safety.

Breaker Pads

These are platforms from where breakers are switched on or off in the switchyard. They are made of reinforced concrete with copper bars on which the operator stands when operating the breaker. The copper bars on the breaker pads are directly connected by copper bars to the earth grid.

Isolator Pads

These are also concrete structures with exposed copper bars connected to the earth-grid where the operator stands when operating the isolator.

EARTH GRID

This is a copper mesh surrounding the substation and also where all equipment is installed dug about 1.5 m deep where all metal work except the conductors meant to carry current is connected. All metal work except the conductors carrying current are earthed for safety.

EARTH RESISTANCE TEST

Before a substation's earth grid is designed, there is need for earth resistance test. Fluke (2024) says that ground resistance is the resistance that exists between a ground electrode and the earth itself. Soil composition, moisture content, temperature and depth of electrodes into the ground impacts on the earth resistance (Fluke (2024)). Ideally ground resistance should be zero, but this is not the case in practice and the resistance is normally 5 Ohms or less. The earth grid should be buried at a depth where it minimizes the earth resistance. According to Fluke (2024), there are 4 methods for carrying out earth ground resistance testing namely:

-

- (1) stakeless testing
- (2) selective testing

- (3) soil resistivity testing
- (4) fall of potential testing.

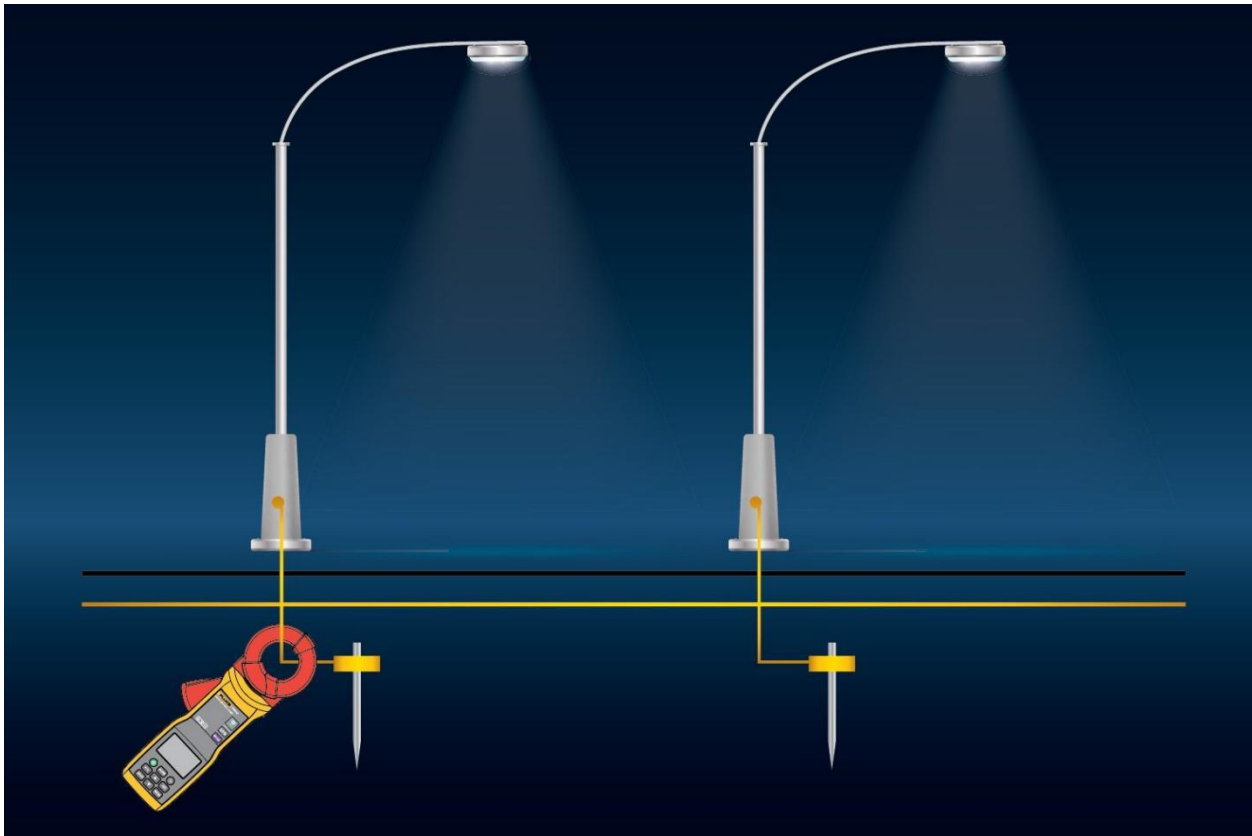
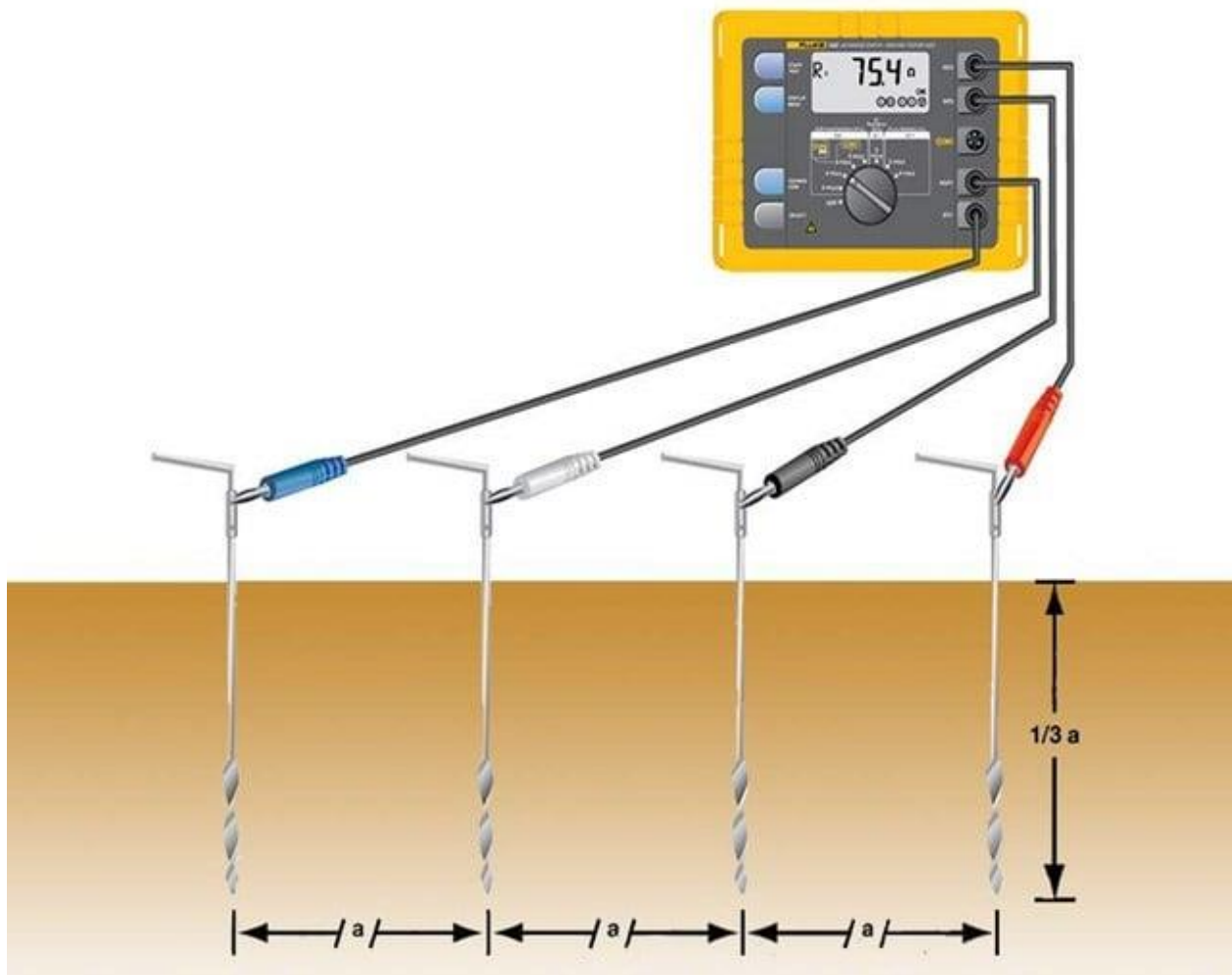


Figure 83 :A minimum of 2.5 m of electrode should be in contact with the soil.



(BIRD'S EYE VIEW) TOP VIEW OF THE STEP UP SUB-STATION

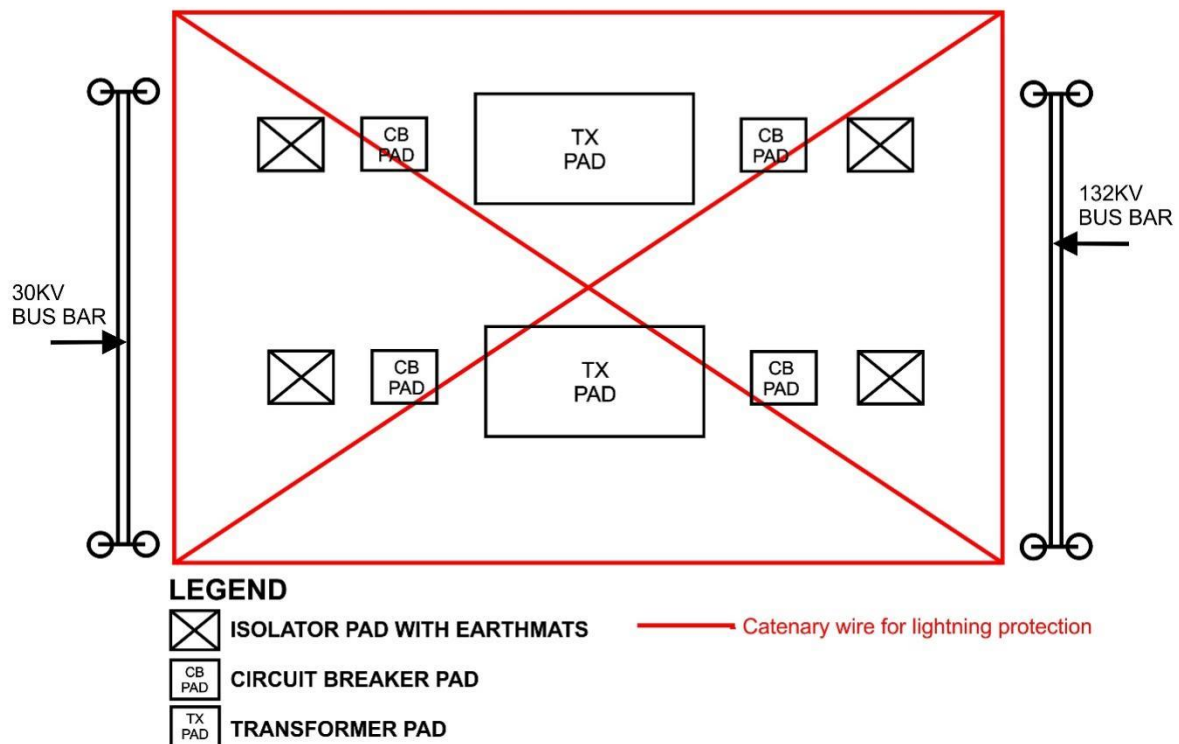


Figure 84

GROUND SITE PLAN OF 30/132 KV STEP UP SUB-STATION

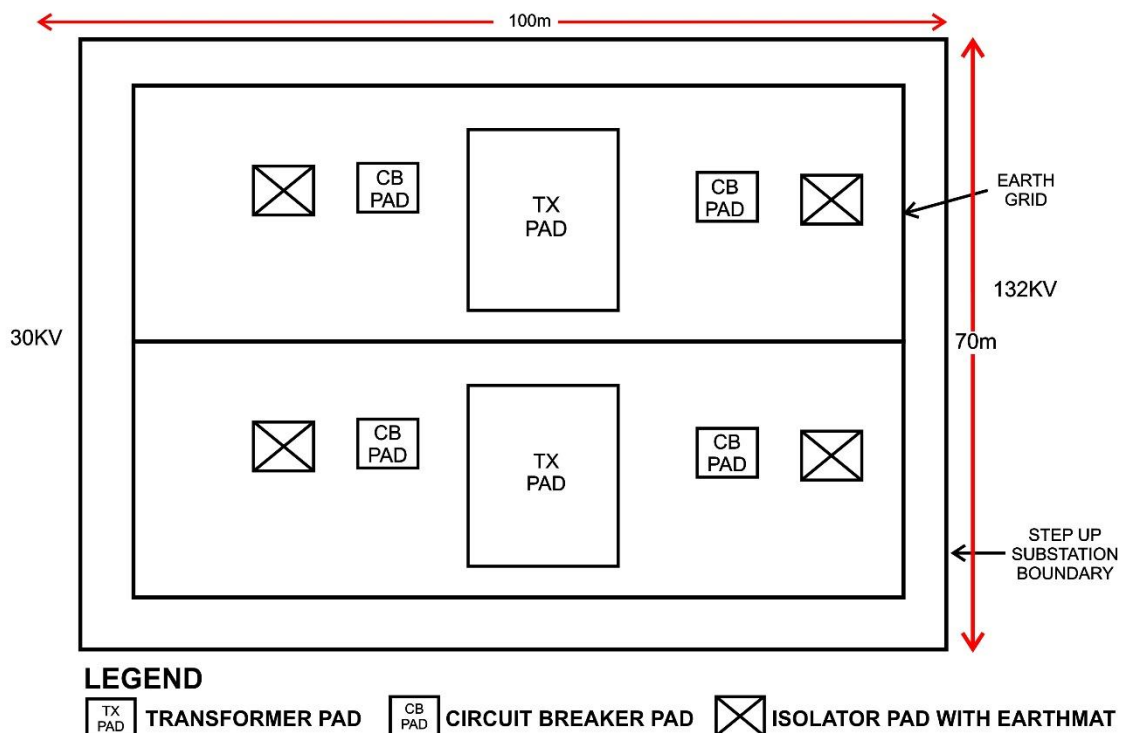


Figure 85

The power station output can be connected to the surrounding 132 KV network or the 330 KV network.

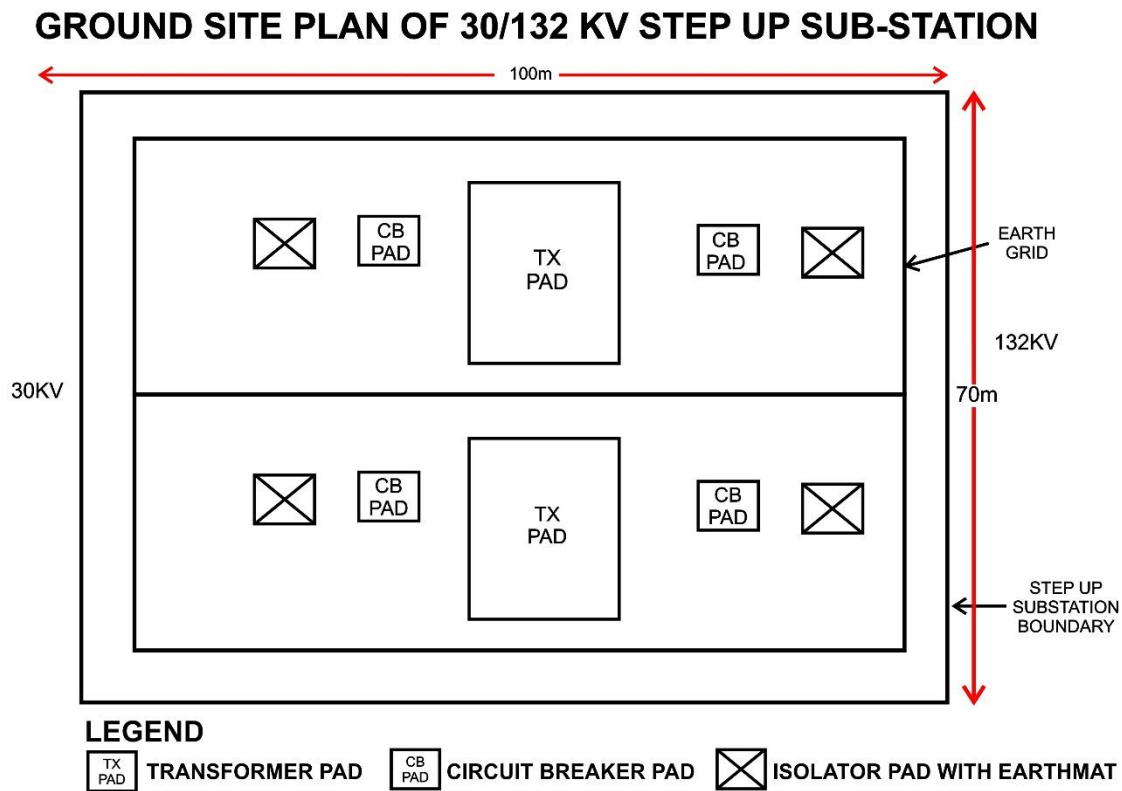


Figure 86

If the Power Station is to be connected to the nearby 132 kV network injection point, the single line diagram will be as follows: -

ELECTRICAL WIRING DIAGRAM OF STEP UP SUB-STATION

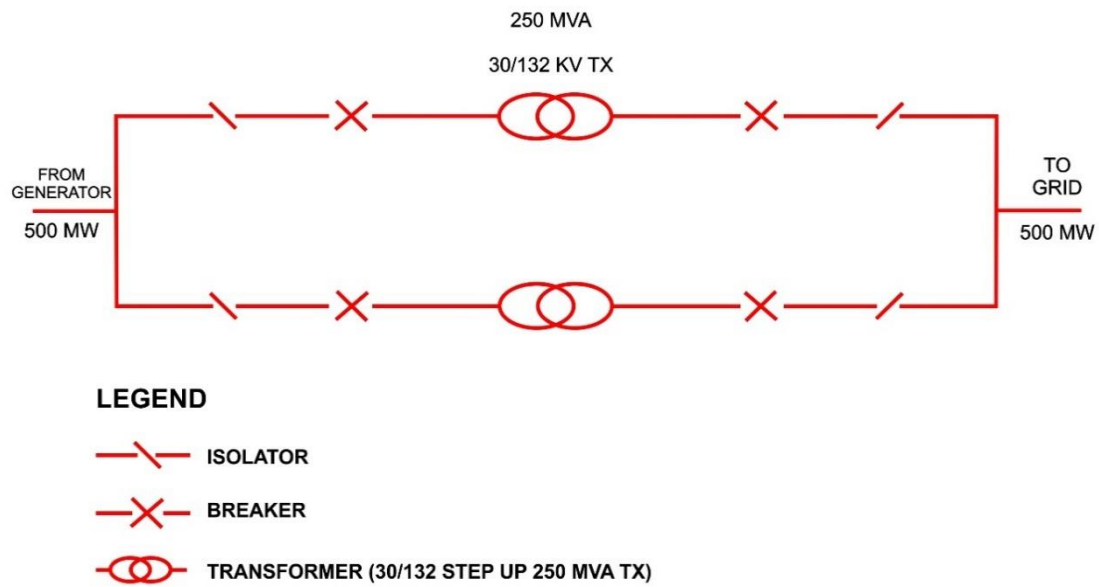


Figure 87

Figure



Figure 88

Above is a picture showing a substation transformer and isolator. Porcelain transformer bushing and tapchanger are also shown.

If the power station is to be connected to the nearby 330 Kv network-grid injection point, the arrangement will be as follows:-

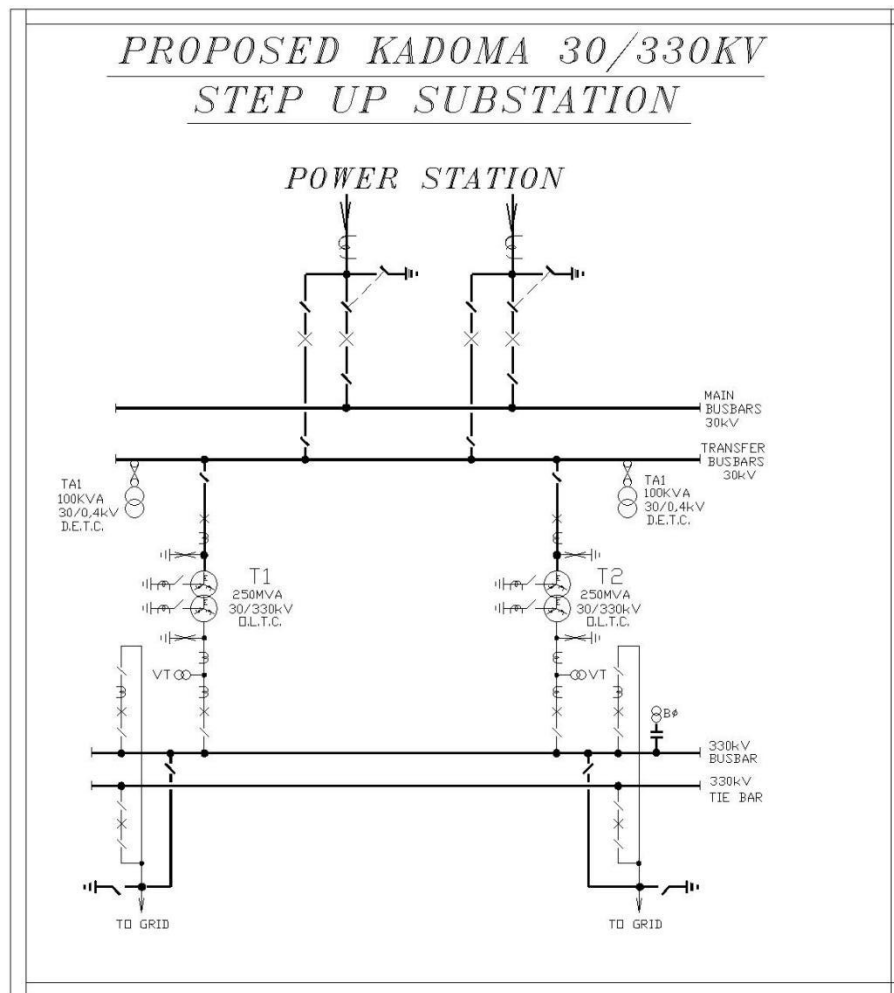


Figure 89

Above is a schematic diagram of the step-up substation showing transformers, isolators and breakers.

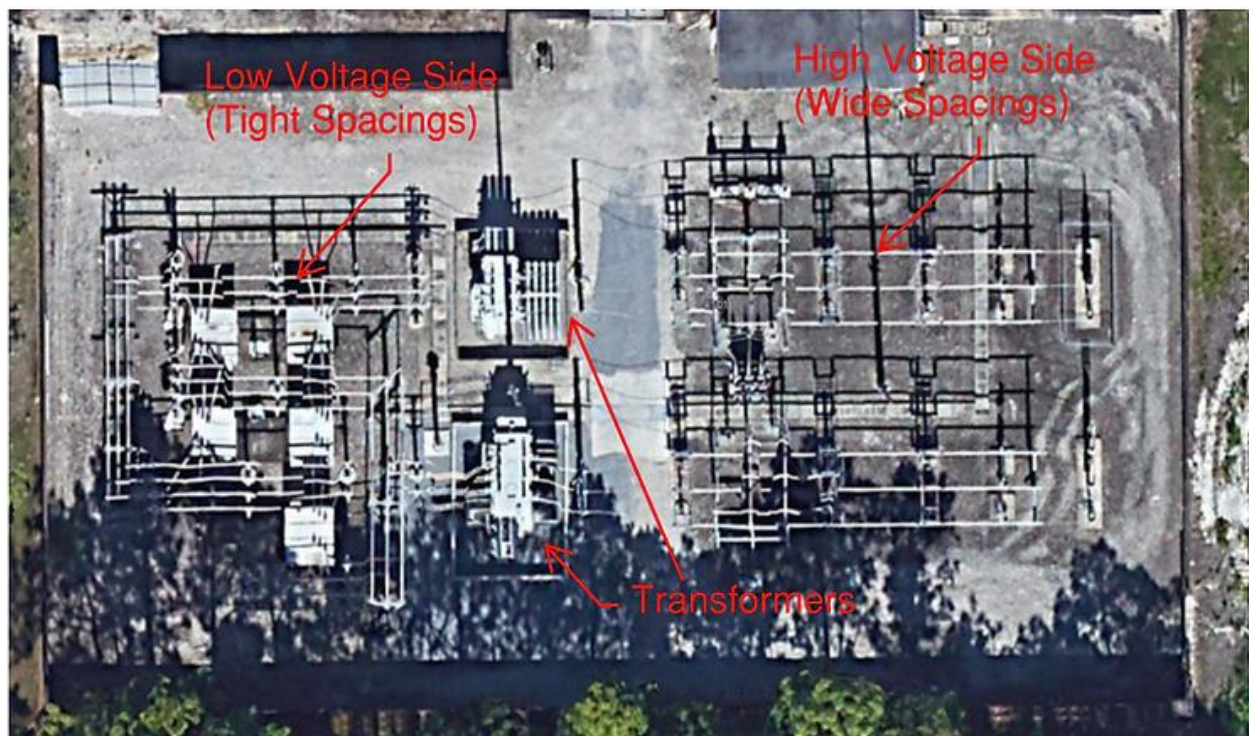


Figure 90

Above is an aerial view of a substation

A tap changer is required on each of the power transformers for voltage regulation. Voltage regulation is the process that maintains the power system voltage in permitted range using the tap changer.

Substations help in facilitating switching, protection, safety and voltage transformations. There must be maintenance accessibility in the substation including drives past transformer bays and breaker pads. There must be allowances for safety clearances and prudent spacing and configuration of equipment. There is need for protection of (a) personnel (b) substation equipment and (c) environment.

According to EEP Academy (2024), relays identify faults and starts protection action for under-frequency, insulation failures and overcurrent and isolates faulty sections by giving trip commands to breakers. Earthing systems avail low-resistance paths to fault currents and minimize risks of electrocutions and electric shocks (EEP Academy (2024)).

Design of Earthing Systems

Before earth-grid design, there is need for soil resistance tests which will guide how deep and wide the earth-grid is to be. There is also need to calculate fault currents, touch and step potential and to follow local regulations with regard to earth-grid and earth-mats.



Figure 91

According to Rao (1992), the major parameters that are subject to measurement include: -

- Active power
- Reactive power
- Voltages

- Currents
- Temperatures on power transformers

POSSIBLE FAULTS ON A TRANSFORMER

- overvoltage (switching surges and lightning)
- overcurrent (e.g. phase to phase fault)
- earth fault (phase to earth fault)

so there is need for overvoltage protection, overcurrent protection and earth fault protection on a transformer

In a substation, there are equipment that require L.V. a.c. supply like (1) motors of circuit breakers (2) lighting circuits (3) air conditioning equipment and therefore an auxiliary transformer is required. A 33/0.4 transformer is required.

The thesis now proceeds to design the Control building for the power station.

3.12 DESIGN OF A CONTROL BUILDING FOR A CENTRAL RECEIVER TOWER POWER PLANT

INTRODUCTION

The problem is that low voltage and extra-low voltage power station control equipment and instruments need to be protected from rain, wind, storms and possible vandalism. To this effect a Control Building is necessary. The main objective of this research is to investigate how a control building can be constructed for an e.g. 500 MW power tower power plant as an example and the professions that may be needed during design and construction of the same. This research focuses on the design of a 2 storey Control Building although many Control buildings are 1 storey. The research involved perusing journals and textbooks on construction as well as observing buildings under construction in Chinhoyi and Kadoma. Visits were also made to Harare power station and Munyati Power Station. Archival research and observational research were the two main research methods employed. The findings in the research includes the fact that various professions and skilled people are involved in the construction of a 2 storey Control Buildings for power stations for example architects, civil engineers, structural engineers, electrical engineers, mechanical engineers, steel-men, civil artisans, bricklayers, builders, plumbers and electricians. The other finding is that for 2 storey power station Control Building columns, beams and bricks connected with cement paste mixed with sand are structural members. The research concluded by positing that power station Control Buildings need to be modernized and made intelligent and if possible multipurpose. Power station control functions may be done on the ground floor and a house constructed on the first floor for technicians and system operators for example as an example of multi-functionality.

METHODOLOGY

The methodology of the research is guided by the research problem, research questions and research objectives which are as follows: -

Problem Statement

The demands for skills needed for the design and building of control rooms is increasing with the demand for energy. Very little literature material covers key concepts in the design and building of control rooms for Central Receiver Tower Power Plants.

Research Questions

1. What is the purpose of a control room?
2. What professions are involved in the design and building of control rooms?
3. What materials are required for the building of a control room?
4. What key drawings are needed in the design of control rooms?

Research Objectives

1. To design a two storey control Building by the end of the research
2. to identify professions needed in the preliminary studies, design and building of control rooms using University of college qualifications by the end of the research.
3. to identify key materials for the construction of control rooms which are non-toxic to builders and operators

BACKGROUND

The power station control room is a building where the monitoring, control and automated artificial intelligence of the whole power station is resident in the form of electronic or electromechanical relays with normally open and normally closed contacts. Depressible, rotatable and push button switches are also available in the control room for remote manual control. Control of the power station variables can be implemented in four ways (1) through relays (2) manually in the control room through available switches (3) in the outside switchyard and also from remote National Control Centre normally in the Capital City. The variables that need to be controlled in a Central Receiver Tower Power Plant includes (1) the solar flux intensity reaching the solar absorber (2) temperatures and pressures in the solar absorber, thermal energy storage tanks (3) rotational speed of the turbine and generator set (4) output frequency of the power station, voltage and power (5) heat transfer fluid flow rate etc. These variables will be monitored through instrumentation in the outside switch yard like pyrometers, barometers, flowmeters, voltmeters, synchroscopes, energy meters, ammeters etc and control through relays in the control room, manually in the control room, in the switchyard or from the National Control Centre.

Temperatures in the solar absorber, thermal energy storage tanks and turbine chamber are measured and monitored through pyrometers. The pressure in the solar

absorber, thermal energy storage tanks, turbine chamber are monitored and measured using barometers. Voltages are measured using instrument Voltage transformers and voltmeters. Currents are monitored using instrument current transformers and ammeters. The turbine's rotational speed is measured using tachometers.

D.C. battery banks will also be in the control room as well as an office with telephones, tables, chairs and computers. Therefore, the purpose of this article is to design a two storey control room i.e. architectural drawings, structural drawings and single line electrical drawings. The building will act as a control room for a 500 MW Central Receiver Tower Power Plants. (1) thermal control room (2) mechanical pressure and rotational speed of turbine and generator room and (3) electrical control room (4) D.C. battery room and an office.

MAIN NARRATIVE

A control room is an essential, indispensable component of a power station as it houses all control, low voltage and extra low voltage equipment. The building needs to be a smart or intelligent building. According to Dakheel et al. (2020), the Energy Performance Building Directive introduced the concept of Smart Buildings in order to encourage user interaction, renewable energy production, reduce energy consumption and energy flexibility. The European Commission report (2019), says that buildings account for 40 % of all energy consumed. In 2010, the EPBD introduced the concept of nearly zero Energy Building target i.e. (a) energy from renewables (b) energy efficient and decarbonized building stock (c) less fossil fuels. Dakheel et al. (2020), says that buildings should be capable of balancing their own on-site energy generation and consumption.

The building should adjust its energy usage to time-of-use electricity prices and its user's utilization profiles, responding to external conditions of weather utilizing prediction control strategies e.g. heating, air-conditioning, ventilation and storage systems. A Building must be able capable of storing and supplying energy and responsive to the needs of the users and the grid i.e. internal and external conditions (e.g. weather and grid). This points towards a subject of Building intelligence.

FEATURES OF SMART Buildings

- automation-capable of accommodating automatic devices.
- multi-function-more than one functionality in a building
- adaptability –integration among users
- energy efficiency in buildings

According to Snoonian (2003), a smart building utilizes information and communication devices to automate building control and operations. They increase occupants, productivity and comfort. They have sensors for control and monitoring e.g. smart ventilation, heating and air-conditioning. Daylighting and dimming to avoid over lit places. Lighting management systems with wire and wireless communication links. Plug loads with miscellaneous gadgets in buildings should completely cut off equipment that is not in use. Sun lighting and globe lighting must be coordinated with window shading. Snoonian (2003) highlights that cloud-based remote building monitoring is rising in popularity.

There is need for buildings interfacing with operators through computer dashboards to capture energy usage, response to load signals, electricity rates, demand response, events and power outages.

Snoonian (2003) posits that smart buildings conserve energy by optimizing systems and automating controls. Snoonian (2003) further says that smart buildings incorporate integrated systems that can save 30-50 % of energy in buildings compared with non-smart buildings.

Hindrances to Prevalence include the following

1. cost of automation which is required upfront
2. the learning curve which is steep for operators and installers

Jia et al. (2019) says that there is need for integration of advanced technologies in buildings for (a) remote operation and control (b) for comfort, convenience, cost and energy saving. Jia et al (2019) mentions sensor deployment, data engineering and analytics, fog and cloud computing, human computer interaction algorithms as necessary. Jia et al. (2019) says that Internet of Things enables objects to understand their environments and can assist in making buildings become smart and intelligent. Jia et al. (2019) posits that Internet of Things has started to penetrate the building sector in the past years.

According to Jia et al. (2019) the 5 main components of the Internet of Things as follows: -

1. terminal sensors and devices
2. communication infrastructure networks

3. analytics
4. cloud
5. actuators and interface

Sinopoli (2010), says that buildings have always been influenced by the technology available and walls and ceilings shall be embedded with sensors.

Sinopoli (2010) posits that a smart building is a building that employs building technology systems to facilitate services and the operation of the building for the betterment of its occupants and management.

Drivers of smart buildings (according to Sinopoli (2010)) are as follows: -

- conservation of energy.
- enhanced system functionality
- technology's continued evolution
- enhanced systems functionality
- integrated systems' positive financial effects

Sinopoli (2010) singles out computing and telecommunications as key in making buildings smart e.g. wire and wireless cabling systems, audio-visual systems, access control systems and video surveillance. Sinopoli (2010) says that technology should not be an afterthought but rather an integral building design driver.

Sinopoli (2010) highlights that building automation, life safety, telecommunications and computing, user systems and facility management systems are essential for smart buildings.

According to Ali et al. (2008), smart and green building design considers sustainability, non-toxicity of building materials, environmental friendliness and aesthetical impact as well as water and electricity conservation. Ali et al. (2008) say, 'Buildings require careful planning, coordination and integration of many professionals and systems. The civil and structural strength of beams, girders, columns, and trusses is of crucial importance to the longevity of the control building. Civil, mechanical, structural, plumbing and electrical professions require coordination. Ali et al. (2008) posits that the site location and orientation of the building in relation to the seasonal and daily trajectory of the sun across the sky has a great influence on the thermal performance and value of the building.

All remote controls of the Central tower power plant are carried out in a building called the Control Building and alternatively from the National Control Centre. Delicate extra-low and low voltage instruments and equipment are protected from wind, rain and possible vandalism e.g. computers, relays, cellphones and d.c. batteries.

Two single gang two way switches may be necessary to facilitate both local and NCC control of the power plant equipment.

When condition monitoring and protection equipment detects a critical or forbidden condition, the relays flags or trips breakers or control the variable respectively. The control room equipment acts as the brains of the power station.

The following diagram shows a closed loop control diagram of a Central Receiver tower power plant where the heliostat focusing, solar absorber temperatures, thermal energy storage tank temperatures, heat exchanger temperatures are to be controlled in order to help regulate turbine-generator rotational speed and therefore MW output of the power station. The Current Transformers(CTs) and Voltage Transformers(VTs) in the below diagram acts as sensors of the power station output power.

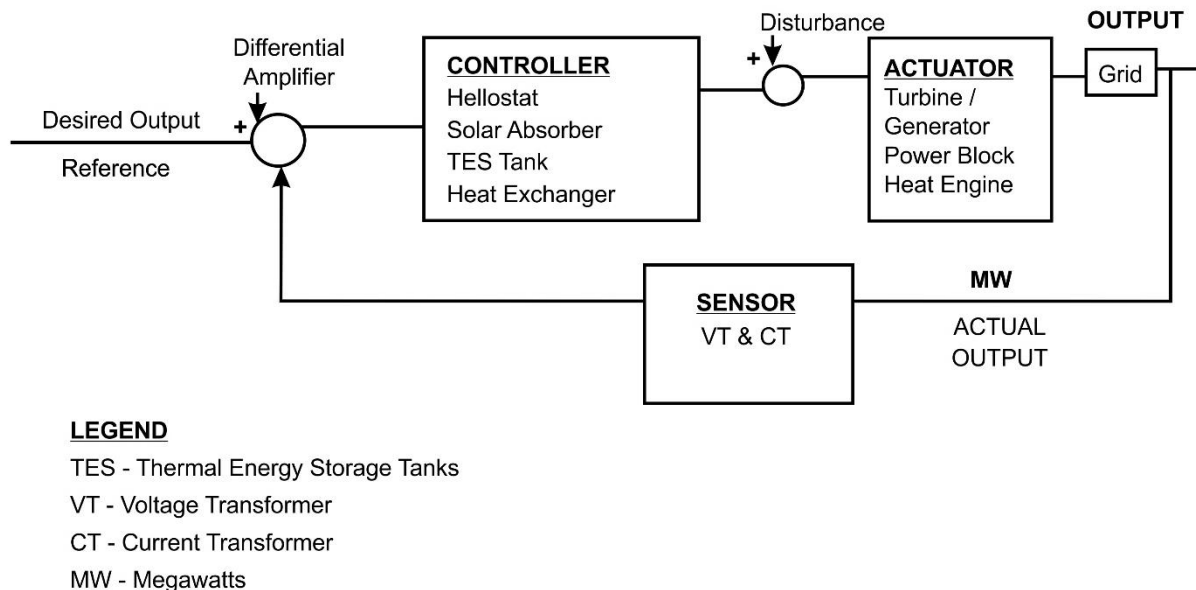


Figure 92

The following controls are accommodated in the control room: -

- focusing of heliostats
- temperatures of the Solar absorber
- pressures and temperatures of the condenser
- TES tanks leak detection, temperature and fluid level
- efficiency of the Heat exchanger (temperature of working fluid and HTF).
- The speed of rotation of the turbine
- the electrical output of Generator (i.e. power, voltage, current, frequency etc.)
- The heat engine/power block efficiency

Architectural Drawings

The architectural drawings are the first engineering drawings to be done and to kick start the building plans. They show sideviews and elevations including top views of floors. Architectural drawings are done by draughtperson under the supervision of Architects or by Architects themselves. The architectural drawings shows the general outline of the building.

Civil and Structural Drawings

These are the second drawings superimposed and developed from architectural drawings. They show columns, beams and steelwork configurations. Plumbing work is also shown in these civil and structural drawings.

Electrical and telecommunication engineering Drawings

These are the last type of drawings to be done after the architectural and civil engineering drawings. They are designed by an electrical engineer showing how conduits and conductors as well as computer and telephone networks are to be configured within the building.

TESTS THAT REQUIRE TO BE CARRIED OUT ON THE SITE WHERE THE CONTROL ROOM IS TO BE CONSTRUCTED.

Electrical

- ***Soil resistivity tests*** are needed to assist in designing and determining the depth of the earthgrid needed for lightning and overvoltage protection as well as for safety to equipment operators.
- ***Structural/Civil for Columns***
- Seive analysis tests- are carried out to determine soil particle sizes
- California Bearing ratio tests-to determine soil strength-hard or soft ground
- Soil plasticity index tests-to determine forces contained within particles
- Sheer-box test-to determine the pressure at which the soil sheer

Structural/Civil for Beams

- to ascertain concrete workability concrete cube test needs to be carried out

The slab that supports a floor is called a 'deck' e.g. First floor, Second floor, Third floor etc excluding the foundation

A deck is a floor separating e.g. ground floor and first floor, second floor and third floor etc but excludes the foundation although the method of installing electrical conduits for plugs is the same for decks and foundation.

LAYING OF ELECTRICAL CONDUITS FOR PLUGS IN THE DECK

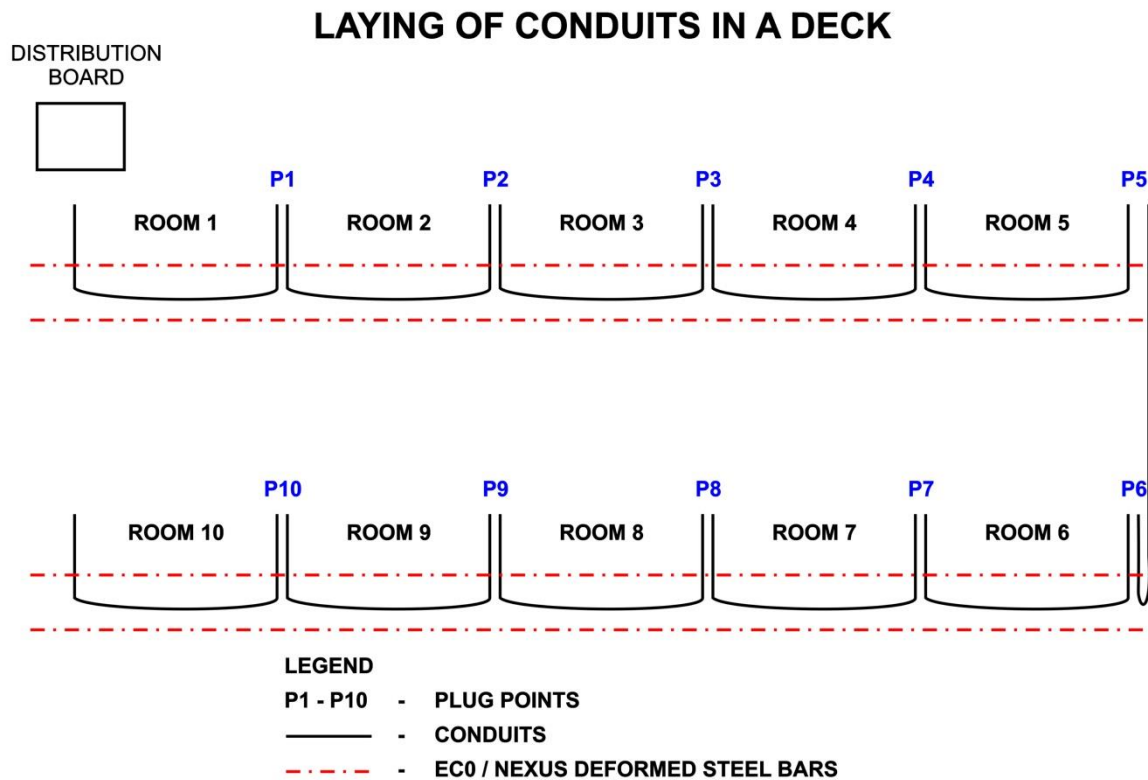


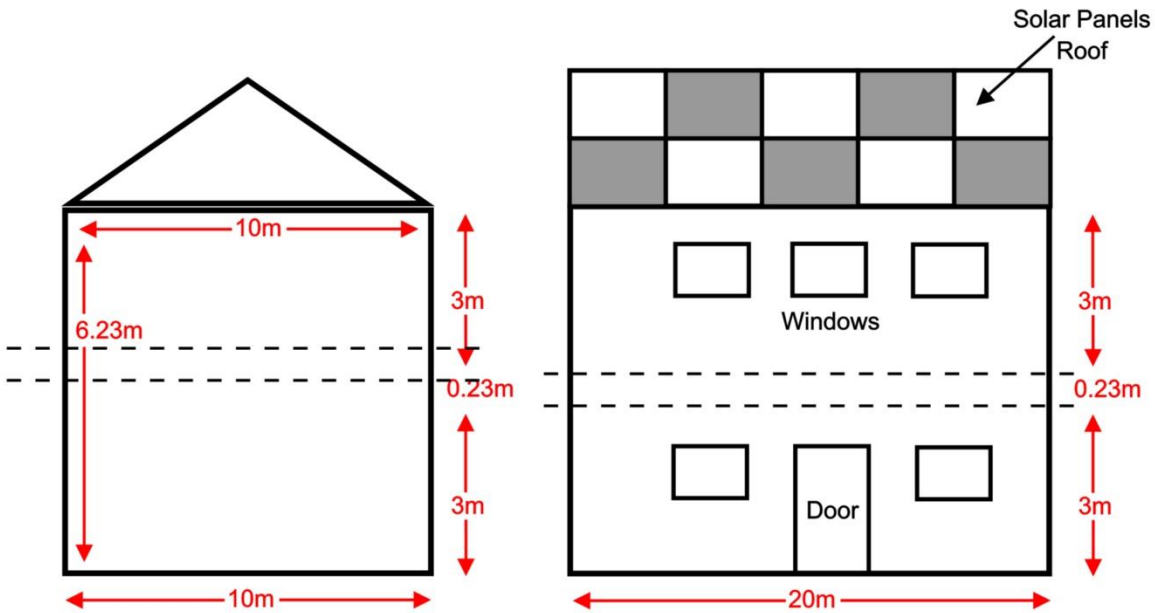
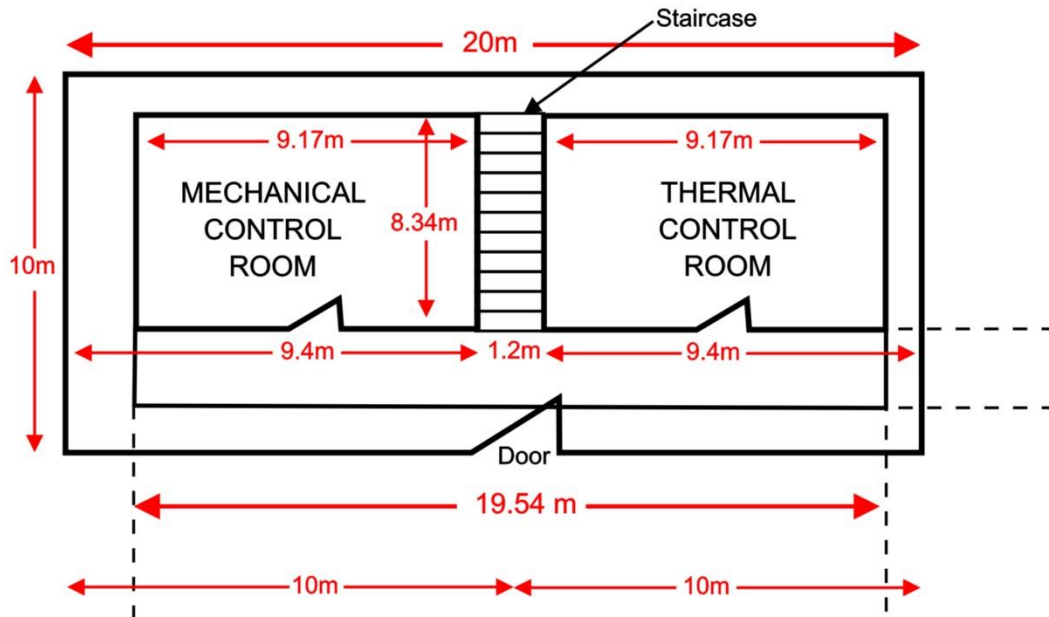
Figure 93

Above are conduit-laying diagram for plugs.

Concrete will be poured on top of the ECO or Nexus deformed steel bars, but the top of the conduits will be left exposed on walls. The first conduit is laid very close from where the floor Distributiobn board is going to be mounted to the next plug point in the first room. The next conduit is laid from this first room plug point to the next plug point in the second room. The third conduit is laid from this second room plug point to the next third room plug point and so forth until all rooms are covered. The top of the conduit maybe bended by a pliers to prevent dust of concrete from going inside the conduit. The conduits need to be elevated to more than 50 cm from where concrete floor is going to be raised to. Plug boxes to be fitted at points P1....P10 in the above diagram.

Architectural Drawings

CONTROL ROOM GROUND FLOOR SITE PLAN



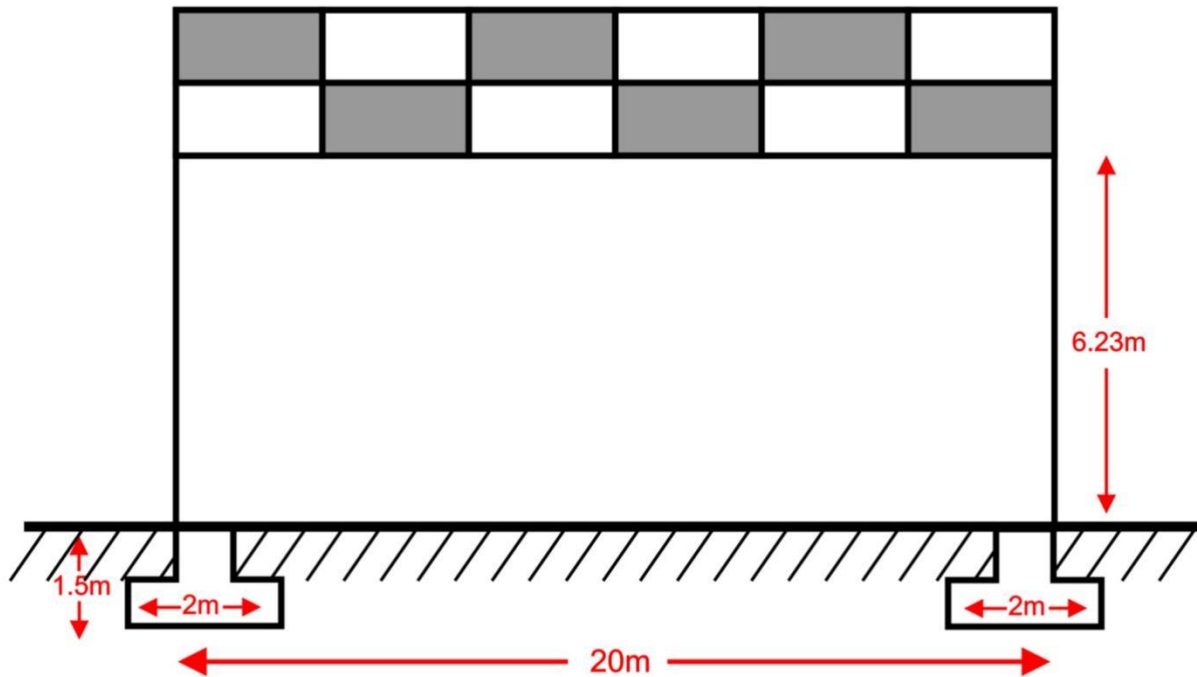
WEST ELEVATION

NORTH ELEVATION

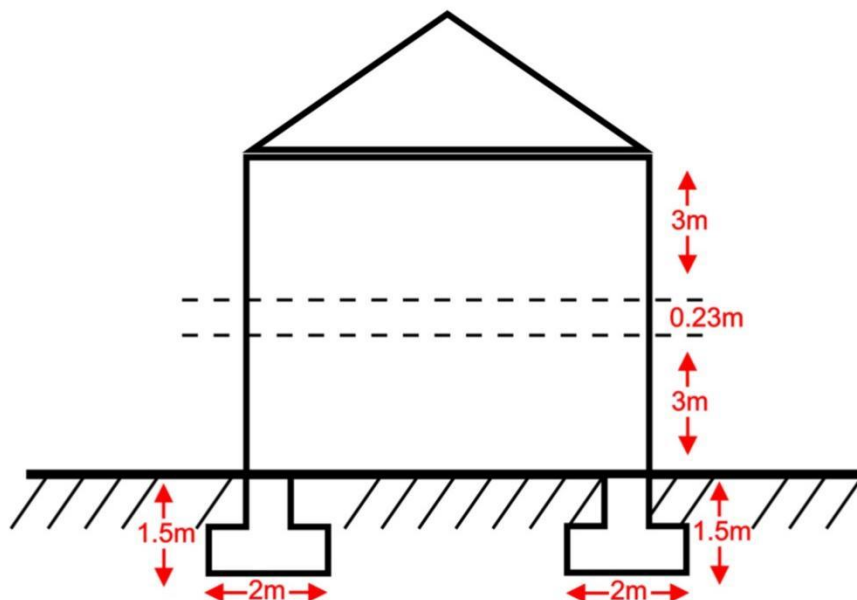
Figure 94

Above are civil engineering site plan, West elevation and North elevation for the proposed Control Building for the 500 MW CRT Power plant

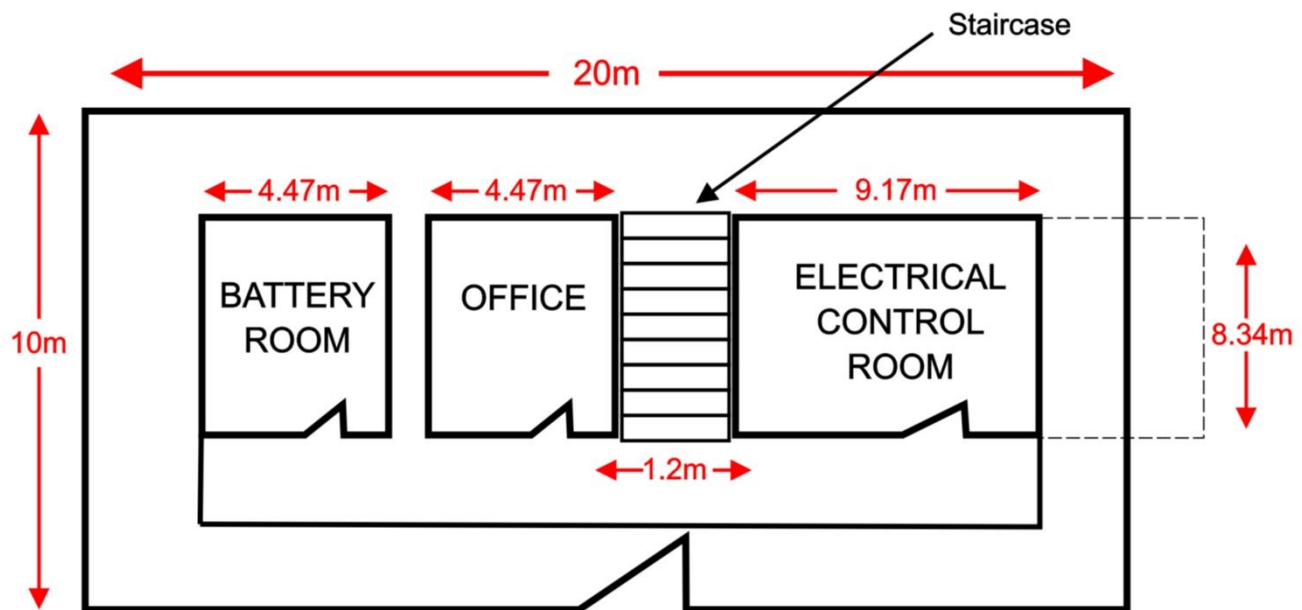
EAST - WEST SECTION



NORTH - SOUTH SECTION



1ST FLOOR SITE PLAN



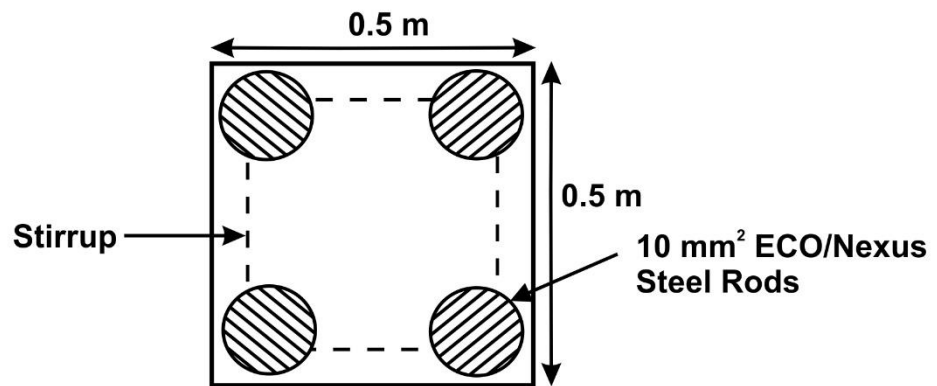
Columns have to be erected at each corner of a room and building or else load-bearing bricks have to be used.

Figure 94

The materials required to build a Control Building includes water, sand, quarry stone, cement, Nexus or ECO deformed steel bars, conduits, 2.5 mm PVC insulated copper conductors, 1.5 mm copper conductors.

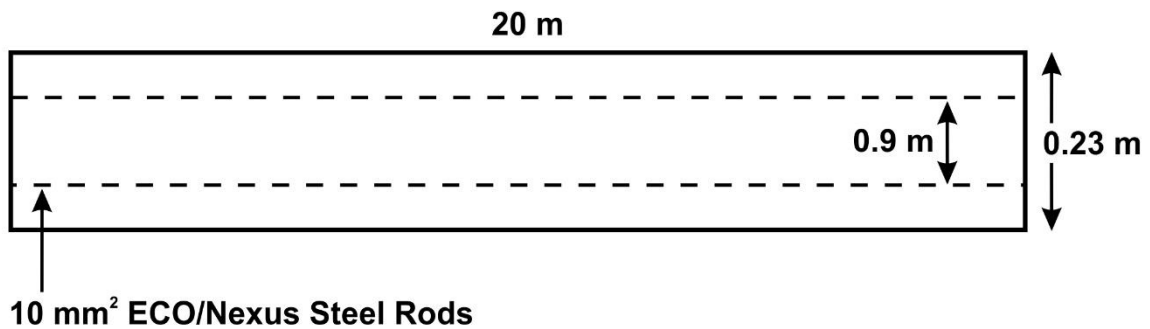
STRUCTURAL DRAWINGS

8 COLUMNS



BEAMS

EAST - WEST



NORTH - SOUTH

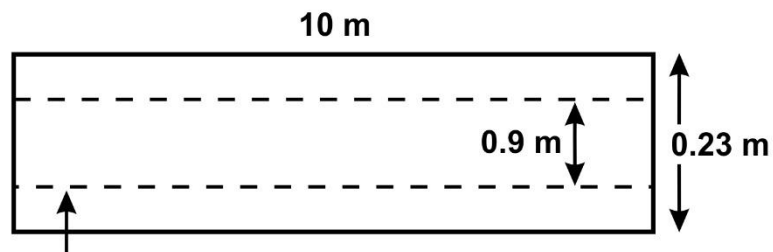




Figure 96

Above is a diagram showing conduit laying for lights called decking –i.e. inter-storey floors

The greyish-brown background on which the conduit round plug and mesh wires are laid above are pieces of metalwork called ‘deck pans’ which are supported by scaffolds After concrete is poured and set after sometime, the deck pans are removed leaving a floating floor supported by vertical walls underneath the sides of the floor and also the vertical reinforced concrete columns.

LIGHTING POINTS CONDUIT LAYING DIAGRAM IN THE DECK

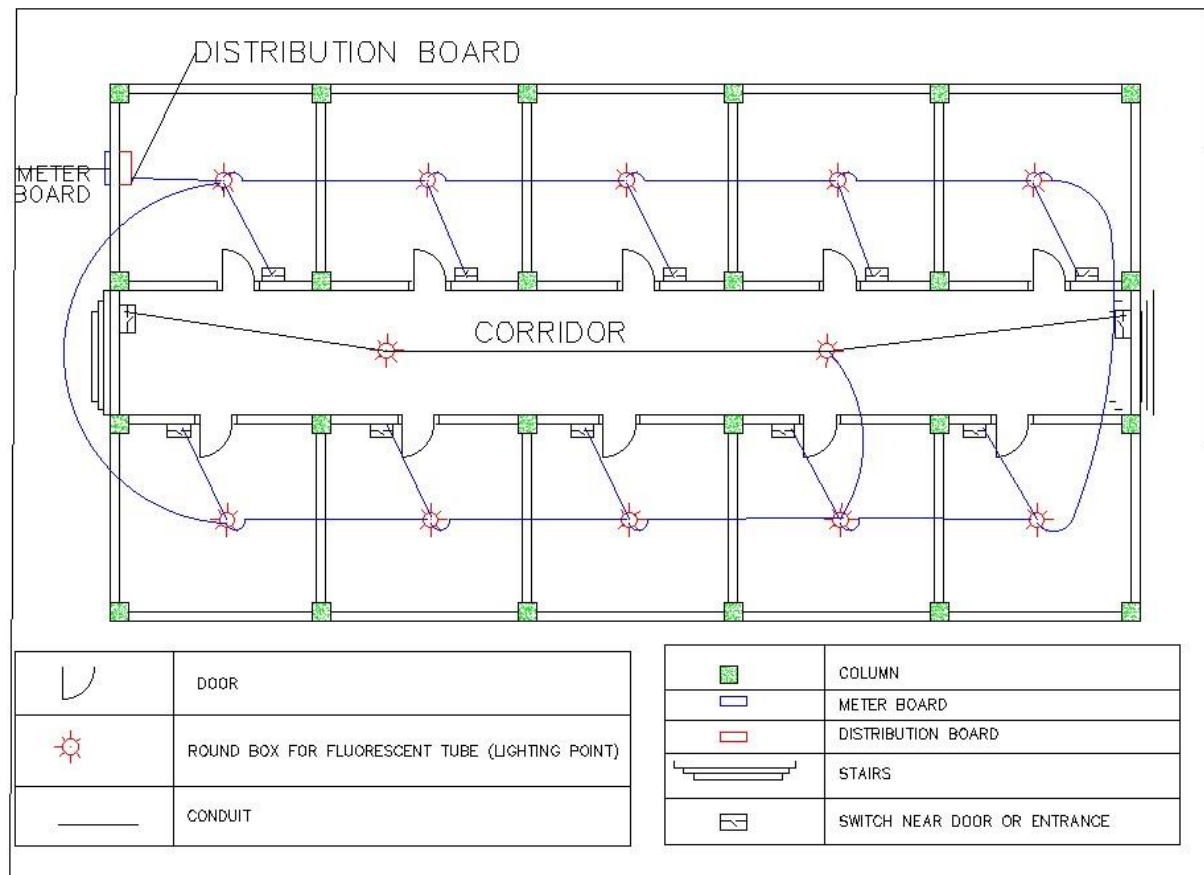


Figure 97

Experience has shown that we need to consider the following when designing a foundation for a building such as a Control Building of a power station: -,

- safety of personnel, materials and equipment during construction
- The building's life expectancy.
- Minimization of costs
- Material saving
- Reduction of construction time.

The steps for designing the foundation of the building are as follows: -

1. Decision on the siting and position of the foundation and columns. There is need to determine the forces likely to act on the building e.g. gravitational forces due to construction materials, wind loads and forces, possibility of earthquakes plus safety factor.
2. Decision on the foundation's depth.
3. Computation of the foundation's area after considering characteristic working loads and allowable pressure.
4. Determination of variation in vertical stresses-to determine depth.

According to Pandey and Kuman (2024), the resistance to shear stress in terms of effective cohesion and internal friction angle is called the shear strength of the soil which is measured using shear box.

According to University of the West of England Bristol UWE (2024), soils on which the control building is to be situated can be classified as (a) hard soil (b) stiff soil (c) firm soil (d) soft soil and (e) very soft soil in terms of soil strength.

The shear strength of soils determines its potential capability to protect the soil against shear forces which results in shear

The shear strength of soils depends on how much compacted the soil is, its particle composition, the amount of voids and water in the soils,

Requirements for Labor

The following professionals will be required in the construction of the control room:

-

civil engineer, steel-man, structural engineer, carpenter, electrician, builder, electrical engineer, plumber, civil artisan, telephone and computer technicians, general hand workers/laborers.

Construction Details

Trenches 2m deep by 0.5m wide are dug to follow the architectural ground floor layout plan. The trenches are filled upto 0.3m with concrete with reinforced steel. Reinforced concrete pillars or columns are erected at each corner of the building from the foundation to the top of first floor. Beams are constructed from steel reinforced concrete on the top of the columns and bricks demarcating top of the first floor. Scaffolds with jacks on bottom and top are used to construct the deck or reinforced concrete floor of the second floor.

A bending bench or table to be erected in front of the stand for bending stirrups for guiding deformed steel ECO or nexus steel rods along columns and beams. We may use 12mm deformed NEXUS or ECO steel rods for beams and 10mm for columns. 2 ordinary and 2 gutter beams to be constructed.

PROCUREMENT LIMITS FOR THE ZIMBABWE ELECTRICITY SUPPLY COMPANY

Description	REQUEST FOR QUOTATIONS	DOMESTIC TENDER THROUGH HEAD OFFICE	Domestic & International Tender
Construction	Upto US\$20 000	Between US \$20 001 & US\$5m	Above US \$5 000 001
Goods	Upto US\$10 000	Between US\$10 001 & US\$300 000	Above US\$300 001
Services	Upto US\$5 000	Between us\$5 001 Upto US\$200 000	Above US\$200 001

TABLE 16

CONTROL BUILDING-WIRING NOTES

To start planning for wiring, one needs architectural drawings for the Control Room showing the floor plan for the ground floor and the first floor. Tubing diagrams are then designed on the ground floor plan and first floor ground plan. From the architectural drawings, we determine lighting points and plug points, their number and positions. The Main distribution board is placed near the local distribution 11/0.4 KV transformer. The switches for lighting points are installed at shoulder level. The plug points are installed 30 to 50 cm from the floor.

Electrical installations consist of four activities namely: -

1. Decking
2. chasing
3. tubing
4. wiring and

5. fittings

DECKING

Floor supporters or slabs or floors that support second floor, third floor e.t.c. are called 'decks' and the process of installing conduits inside these floor or decks is called 'decking'. Conduits are placed in between ECO or Nexus steel rod meshes that are then later covered with concrete. The foundation of the building supporting first floor is not a deck. Conduits are bended using conduit-benders and connected on the round-boxes using nipples and couplings. The round-boxes where lighting points are to be installed and made to flush with decking pans using stones

CHASING

Electrical conductors or wires are pulled and stay inside electrical conduits. Conduits provide mechanical protection against damage to electrical conductors and their insulation. In order to guarantee flush mounting with the walls, small grooves or tiny rivers, streams or channels are dug inside walls or floors using chasing hammers or grinding machine together with chisel and hammer. The process of creating small streams, grooves or channels along walls of a building is called 'chasing'. Chasing is required for flush mounting installations where conduits are hidden in the walls and not required in surface mounting installations where conduits are seen by all in the building.

TUBING FOR PLUGS

The first conduit is run from the Distribution Board to the first plug point. A conduit is then run from the first plug point to another plug point to another plug point to another plug point to another plug point upto a maximum of eight.

Wiring-Lighting Circuit

LIGHTING CIRCUIT

LEGEND

 Distribution Board

 Switch

 Globe / Lighting Point

 Live Wire

 Neutral Wire

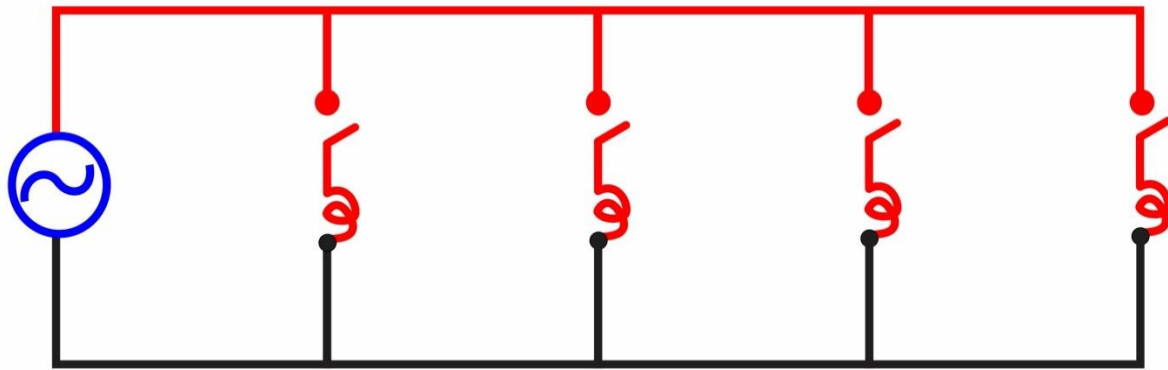


Figure 98

PLUG CIRCUITS

LEGEND

-  Distribution Board
-  Plug Point
-  Live Wire
-  Neutral Wire
-  Earth Wire



Figure 99

LIGHTING CIRCUIT

LEGEND

 Distribution Board

 Switch

 Globe / Lighting Point

 Live Wire

 Neutral Wire

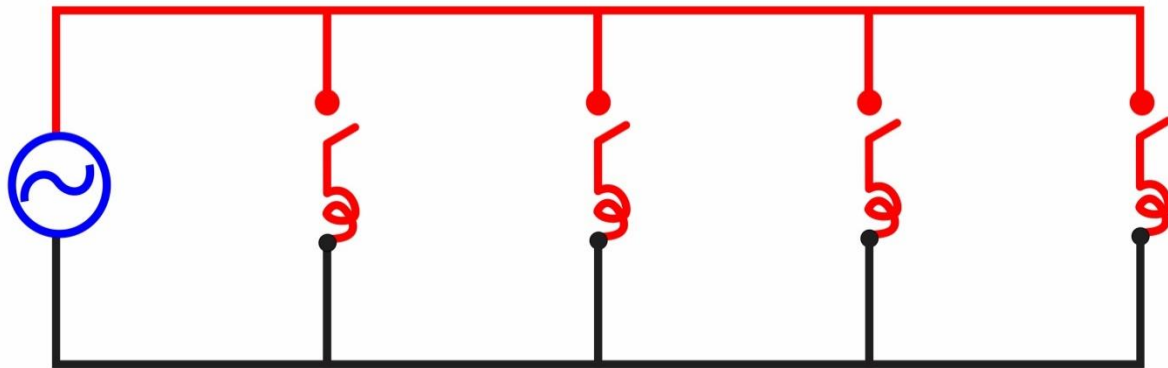


Figure 100

And three conductors for plugs

Live(red), neutral (black or blue) and earth (yellow or green)

PLUG CIRCUITS

LEGEND

-  Distribution Board
-  Plug Point
-  Live Wire
-  Neutral Wire
-  Earth Wire



Figure 101

Connections are done at the (1) meter board (2) distribution board (3) plugs (4) lights

ARCHITECTURAL DRAWINGS AND CIVIL ENGINEERING

As mentioned before, Architectural drawings highlight (a) the ground site layout plan (b) north and south elevations (c) West and East elevations

Civil engineering drawings mainly highlight structural drawings e.g. the foundation of the control room needs to be 1.5m deep. The beams and columns reinforced with deformed NEXUS or ECO steel rods are shown on the civil engineering and mechanical drawings.

Stirrup brackets need to hold the steelworks on beams and columns spaced about 20 cm apart. Electric conduits and pipes for sewer need to be inside steel rods and

therefore concrete pillars (columns and beams) with lower and upper ends emerging from the columns and beams.

Responsibilities in the Construction of a control-room

- (1) A construction company owned by a civil engineer does the civil engineering drawings from architectural drawings. It also does the brickwork construction
- (2) The Decking, plumbing and scaffolding engineering company owned by a structural engineer or mechanical engineer also do the steelwork for decking, plumbing and scaffolding erection. Scaffolds have jacks on both the bottom and top side for stability and balance of horizontal and vertical forces.
- (3) The Electrical Installation company owned by an electrical engineer does electrical engineering drawings as well as communication and computer networking installations.

Duties of Mechanical Engineer during the building of a control room includes: -

- Designing, installation and construction of ventilation, heating and air conditioning of the building.
- Design of plumbing i.e. sewer and water reticulation in the building
- Fire alarms and access control e.g. doors and windows

You need to procure the following materials

- 1.5 mm, 2.5mm, 6mm and 10mm copper wire cables
- Distribution board(DB)
- Meter board
- Conduits
- Couplings and nipples
- Cooker and spreag tube

The distribution board need to be installed in the passage.

For lighting circuits, you use a 5A MCB Main circuit breaker). For plug sockets use a 20A MCB on a circuit.

From Distribution board go to 1 circuit. You tube to one circuit until your circuits are complete. Tube according to circuits then you wire. Tube (conduit installation) first. For wiring use fish tape. Tubing bending is a special skill.

When wiring for lighting you go from 5A MCB with your live from DB to the nearest switch point with your feed until your circuit is complete.

You take your neutral from DB to nearest light point until to the last 8 lighting point, light to light, light to light.

From your switch you need a live switch wire to your light. When you light it lights up the light switch wire.

Every circuit should have an earth wire connecting every metal point on the lights and plugs

On high-rise buildings you have 3 phases red, yellow and blue as rising mains from ground floor up-to the 20th floor (or whatever floor the building ends). The sizing of the rising mains depends on expected load (total building load). The connection of floors must alternate on the phases to ensure phase balance.

If the control room for the were to be actually constructed using local experience, the costs may be charged as follows.

ACTIVITY	NUMBER OF DAYS(DURATION)	APPROXIMATE COST (US \$)
Chasing	2	\$300
Tubing	1	\$100
Wiring	2	\$400
Fittings & Connections	0.5	\$50
Installation of Meter Board & Distribution Board	1	\$200
TOTAL	6.5	\$1 050

TABLE 17

Connections are done at the (1) distribution board (2) meter board (3) plugs (4) lights

Solar Rooftop solutions

You choose a certain convenient corner for placing your battery Bank. The batteries should have the same voltage and current output as the panels. Batteries should be

placed where there is no traffic e.g. the top floor above room. The batteries and inverter needs ventilation. The inverter and the batteries cannot be installed in a where there are hot temperatures The connections from the batteries and solar panels are connected to the inverter for it to convert d.c. output to a.c. The output from the inverter meets with power utility supply in the Distribution Board. The inverter is sensitive to lightning and needs to be grounded through lightning arresters. There is need for lightning arresters to protect the inverter from lightning strikes.

There is need for a connection from the power utility (ZESA) Distribution Board to inverter for charging the inverter and batteries from ZESA mains. Inverter back to ZESA., solar panel to inverter, common from inverter to Distribution Board. Batteries and Solar panels are connected in parallel.

There is need for 3 Wires: -

- solar panel to charge batteries
- ZESA (power utility) through inverter to charge batteries
- power from panel or panel back to Distribution Board (to house lights (

There is need to select and set the inverter if there is sun as first choice so that if there is sun, it gets energy from the sun. If there are no clouds, the solar panels charge ZESA automatically. If there is no ZESA and its cloudy, the batteries though the inverter supplies the control room.

SOURCES OF SUPPLY TO control room

1. Power utility (ZESA)
 2. Solar Panels
 3. Batteries
- Inverter is set

Solar panels or alternatively batteries alone should be able to supply house (lights and plugs)

The regulator can tell you when the battery is full. We need solar panels, regulator, batteries and inverter

LIGHTNING PROTECTION

A copper rod needs to be installed on top of the building and connected through a copper wire to the power station and substation earth-grid for lightning protection.

AREAS FOR FUTURE RESEARCH

Areas for future research in the design and construction of Control Buildings include the following: -

1. Lightning studies and plotting of isokoraunic lines for locating power tower power stations in high lighting strike areas for possible trapping of lightning energy and transforming it to be exploitable for commercial use.
2. How to incorporate artificial intelligence, artificial neural networks and cloud computing in order to enhance the intelligence of Control Buildings for power stations.

CONTRIBUTION TO WORLD BODY OF KNOWLEDGE

Apart from plumbing pipes and electrical conduits, telecommunication and computer networking trunking material need to be installed in decks, walls and floors during construction to be integrated from the start of design, construction and commissioning of the Control Building.

KEY ASSUMPTIONS

- 1 Cement to sand to water ratios are as per British standards in making brick paste
- 2 The control building will remain intact forever
- 3 Qualified builders will be used in the Construction of the Control Building
- 4 Qualified and experienced electricians will be used in doing electrical fittings

CONCLUSIONS

The efforts of architectures, structural engineers, civil engineers, electrical engineers, mechanical engineers, telecommunication engineers and computer engineers as well as civil artisans, steel-men and electricians in the design and construction of the building to be used as a control room needs to be planned, coordinated and synchronized for efficiency and effectiveness.

The first to exert effort is the architecture and his draftsman who prepares architectural drawings. The civil engineers then prepare structural drawings. The mechanical engineer moves in with plumbing and ventilation designs. The electrical engineer prepares conduit laying diagrams and wiring diagrams for the building. The telecommunication engineer and the computer engineer also makes provisions for incoming telephone lines, internet service provider's incoming lines and decides which rooms to install PABX and which rooms to be used as computer rooms.

Soil tests may need to be done by the civil engineer in order to design the foundation for the building and whether special foundations are required.

The builders, plumbers, civil artisan and steelman does the actual construction and the electrician does the actual electrical installation.

The electrician does the chasing, tubing, wiring fittings and connections for electrical, communication and internet lines.

The next section is on Instrumentation and Measurements.

3.13 Instrumentation, Measurements Sciences and Control Issues and Considerations in the designs of CSP Power plants of the Central Receiver Tower type for optimal System Operational Efficiency

INTRODUCTION

Green energy is now regarded as modernity in electricity generation methodologies because of climate change issues, depletion of the ozone layer, toxicity of coal dust and some toxic elements associated with coal mining such as Sulphur. Concentrated solar power stations are one way of supplying green and renewable energy to a power utility grid and therefore ultimately utility customers who hopefully will be delighted with the quality of electricity supply. The power plants need instruments for measuring parametric variables therein. These measurements need to be monitored and used in the control of those variables and hence this paper highlights critical issues arising therefrom such instrumentation, measurements and control of such critical CSP plants in particular of the Central Receiver Tower type. There is also need for real-time digital telecommunications communications between the constructed CSP plant and the National Control Centre of the power utility concerned normally in the Capital City of the country concerned like in the Case of Zimbabwe-Harare. Control of measured variable parameters (measurand) need to be controlled both locally or remotely from the National Control centre and this paper reports on how this may be achieved.

MAIN NARRATIVE

3.13 MEASUREMENT SCIENCES, INSTRUMENTATION AND CONTROL SYSTEMS OF A CENTRAL POWER TOWER POWER PLANT/POWER STATION.

If we cannot measure that which we are talking about, then we do not have adequate knowledge of it and we cannot effectively control it! Measurement sciences mainly touches on the subjects of instrumentation, sensors and transducers. Measurement sciences is the backbone of real-time power plant monitoring, control and therefore protection systems. Measurement fidelity is the foundation of accurate, precise, timeous and exact control of an industrial plant such as a CSP power station. Measurement sensitivity and control dynamics determines the speed and accuracy of supply and demand-following of a CSP of the Central Receiver Tower power plant.

Measurements are important for the following reasons: -

- System monitoring, control and protection
- Post disturbance analysis
- Monitoring of inter-area oscillations
- System modeling

There is need to integrate information systems, computing, digital communications, control and automation with measurement systems for effective operation of CSP power plants.

There is need for us to be able to measure the quality and quantity of electricity output of the central tower CSP power plant and use it as the overall control parameter of all upstream variables such as absorber/receiver temperature, turbine speed, HTF flowrate, storage tank temperatures etc. Instrumentation or sensors which detects, measures and quantify these variables is essential for the control of these variables.

We can represent components of the central tower power plant using block diagrams of signal flow diagrams according to Dorf and Bishop (2014: p25), in their textbook entitled Control Systems.

According to Dr. Pandey (2018), 'Instrumentation is the study of detection, acquisition, control and analysis in all areas of science and technology.'

Sensors and transducers are used in the automation of processes such as power plant operation optimization and efficiency enhancement e.g. in CSPs. Very accurate control of power plants, processes and systems demands that we be able to accurately measure, track and control these variables.

According to Dr. Pandey (2018), 'Sensors and transducers have helped achieve substantial accuracy and control and automation of any kind. Such endeavor begins with the measurement of certain system parameters/variables such as solar flux, temperature, turbine speed, heat transfer fluid (HTF) flow rate of which sensors and transducers form an essential and indisputable part. After measurement, control of each measurand in order to have quality output is then necessary.

Sensor: is a device which detects a change in input energy to result in a change in another same form of energy.

TRANSDUCER

A transducer is an instrument which transforms one form of energy into another form of energy e.g. heat energy differential to electricity (e.g. a thermocouple or pyrometer) mechanical energy to electricity, chemical energy to electricity, temperature to electricity etc.

A transducer detects the quantity of a variable to be ascertained or measured and transforms it to a proportionally suitable signal which is preferred to be electrical in form.

The measured quantity is invariably disturbed by the measurement process and system. All transducers take some energy from the measured medium. A perfect measurement is therefore impossible theoretically.

As mentioned before a transducer is a gadget which transforms one form of energy into another especially from other forms to electrical energy. It provides an electrical quantity as a result of detecting another form of energy or a physical quantity, mechanical quantity, thermal quantity, chemical quantity etc. The measured quantity

can be mechanical, optical, thermal, chemical but the output is electrical. Transducers use transduction principle to provide an electrical output in response to a specific measuring from another form of energy, e.g. a photodiode converts sunlight or light energy into electricity.

The main advantages of getting an electrical signal as output are as follows according to Dr. Pandey (2018): -

1. Electrical signal can be amplified easily.
2. Electrical signal can be easily indicated, recorded or displayed.
3. Electrical signals are not affected by inertia and friction unlike sensors with mechanical outputs.

Resistance thermometers or pyrometers based on the principle that variation in temperature varies the resistance of pure metal wire will be used to measure the temperatures of the receiver and thermal energy storage tanks of our CSP central power tower.

A heat-sensitive resistor-photoconductive cell. Incident light varies the resistance of the cell as a circuit element.

A potentiometer.

Piezoelectric effect: When an external force is applied to certain crystalline material such as quartz an emf is generated-this can be used to measure pressure e.g. in steam going into the turbine.

The voltage is generated due to motion of a coil in a magnetic field! This principle is used in the generator to convert rotational kinetic energy of the turbine into electricity.

A thermocouple –An emf is generated at two ends of two metals or thermoelectric materials if a temperature gradient is established at their junction and their ends. This is now also a new method of generating electricity-thermoelectric generation.

The variables from the CSP power plant like

- (1) generator voltage, current and therefore output power measured using current transformers and voltage transformers or energy meters
- (2) turbine speed and rotational kinetic energy measured using tachometer.
- (3) Flowrate and speed of steam into turbine measured using flowmeter
- (4) temperature in the hot and cold thermal energy storage tanks measured using pyrometer
- (5) flow rate of HTF from receiver/heat absorber to tanks measured using flow meter
- (5) solar insolation level measured using photodiodes

all need to be converted to electrical outputs. The resultant electrical signals will normally be analog signals which need to be transformed into digital signals employing an analog to digital converter(ADC) for inputting into a computer with a control program. Commands from the computer to actuators and controllers including the plant also need to be converted to analog signals before going to components concerned! The computer will have an operational information system!

Central Receiver Tower Power Plant



Figure 102

MEASUREMENTS

The paper posits that measurement of all variables in any industrial process such as a CSP power plant is imperative, compelling, necessary and vital for accurate analysis, monitoring and quick control of those variables. Accurate, precise and fast control of the output of a CSP power plant is needed in order to fine tune the output energy so that high quality electricity may be produced that may hopefully delight the power utility customers and end-users. According to Prasad (2004), knowledge greatly depends on measurement and the technology of measurement called instrumentation. According to Gupta (2015), measurement is the result or act of a quantitative comparison between a given quantity and a quantity of the same kind chosen as a standard or a unit. Measurement enables us to have a means of describing

a natural phenomenon in quantitative terms. Instrumentation is the technology of measurement. An instrument may serve as a component of an automatic control system. We measure (e.g. solar absorber temperature, flowrate of the Heat Transfer Fluid, turbine rotational speed and output power) in order to monitor, control and automate the output of the CRT power plant. Control of a variable is necessary in order to fine tune its value to a desirable quantity and quality. This paper therefore reports findings from existing literature consulted so far on the subjects of instrumentation, measurement and control of industrial processes and goes further to adapt those concepts and principles to a CSP power plant of the Central Receiver Tower Type

The paper highlights that in order to monitor, analyze and control parametric variables within a CSP power plant measurements are of supreme value. The tridimensional attributes above are the main reasons for carrying out measurements in a CSP power station.

Prasad (2004), highlights that there are 2 classes of measurement direct measurement and indirect measurement. Prasad posits that in direct measurement schemes, the quantity to be measured and sized is compared directly against a standard of the same type of quantity e.g. length may be measured in terms of meter and a numerical constant.

Current is a typical example of an indirect measurement method where a deflection of a pointer on a scale corresponds to the current (Prasad (2004)). Thus the current is not compared with a standard current, but rather converted into a force which causes the pointer to deflect.

Most variables to be measured e.g. pressure, temperature, flowrate, turbine rotational speed are converted to electrical signals e.g. thermocouple to measure temperature because the electrical signal is a versatile quantity which can be attenuated, amplified, modulated, rectified, measured, modified, transmitted and or controlled. Prasad (2004) says that the above fact of versatility created the interest to use electrical methods to measure non-electrical quantities such as temperature, pressure, flowrate, turbine speed and solar flux in a Central Receiver Tower power plant if effective automation and control is to be achieved. Electronic measurement systems have higher versatility and make them more popular.

Monitoring.

Pyrometers are needed in the Central Receiver power plant for the purposes of monitoring temperatures in the solar absorber, thermal energy storage tanks and the heat exchanger. Flowmeters are required in a CSP power plant for monitoring flowrates in the HTF flow tubes between the Solar absorber and the thermal energy storage tanks and between the tanks and the heat exchanger leading to the heat engine or power block. A tachometer is necessary in order to monitor the rotational speed of the turbine/generator set. Barometers are vital in order to measure steam pressure to turbine blades. Energy meters are needed in order to monitor output energy in MW from the CSP power Plant.

Control

After monitoring the variables in a CSP as mentioned above electric pumps are required in order to control flowrates mentioned above. Heliostat assembly 'heat-focus' or pointing accuracy on the solar absorber may be reduced or increased i.e. varied in order to control temperatures in the solar absorber after getting control signals from pyrometers and CCD cameras mentioned above. The steam pressure to the turbine blades as indicated by barometers may be adjusted by varying steam output to turbine blades by adjusting steam governor valves. B/W CCD cameras are needed to monitor heliostats aim points for even distribution of heat on the receiver surface and minimize spillage. The sun vector found using 4-quadrant photo-sensors at one point is needed in order for controlling computers to calculate the bisector of the sun-heliostat-receiver angle for positioning of heliostats. Control of power plant variables is not only done to ensure quality output power, but to also protect plant components from damage as well.

Analysis

Measurements are also made to: -

1. Validate predictions & forecasts from theories.

2. Construct empirical models and prototypes, i.e. relationships between parameters and quantities associated with a problem and
3. Characterize materials (e.g. thermal energy storage materials) for CSPs), devices and components.

In general, these requirements may be called analysis.

According to A. K. Ghosh (2010), a generalized instrument consists of the following (a) a transducer (b) a recording or display gadget (c) signal conditioner. A transducer transforms one form of energy into another for example a pyrometer transforms heat energy into electricity using the thermocouple principle. Transducers subtracts or extracts part of the energy from the measured medium. The measured attribute is invariably altered by the measurement process. This implies that a perfect measurement is theoretically impossible.

Signal Conditioning

According to A.K. Ghosh (2010), the signal from the measuring instrument's transducer may require attenuation, amplification, integration, differentiation, modulation, conversion to digital signal etc. The signal conditioner performs this function.

Signal transmitters may be necessary for remote measurements e.g. CRT measurements to National Control Centre in Harare.

For CRT power output control, we may only control the following: -

- The focusing accuracy of the heliostat mirrors onto the solar absorber
- The HTF flowrate from absorber to Energy storage tanks & from tanks to heat exchanger
- Electric motor pumps rotational speed
- Steam pressure and hence rotational speed of the turbine-generator set

Instruments

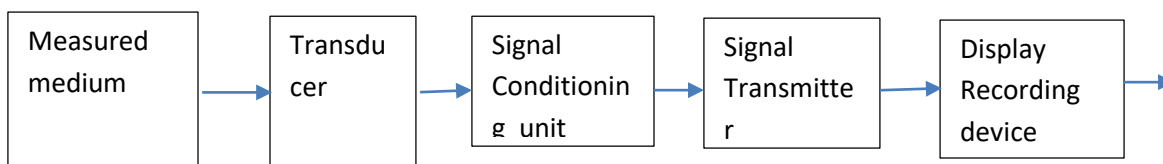
Measurements are facilitated by the help and use of instruments. Instruments generally consist of a small number of elements.

As mentioned before an Instrument: is a gadget or device which is made in such a fashion that it maintains an operational relationship between a given property of a substance and a variable and communicate this relationship to a person observer or control electronics gadgets like programmed computers by some method or means.

For example, a pyrometer in a solar absorber is an instrument because it maintains a linear relationship between current of electricity output from the pyrometer (prescribed property) and temperature in the solar absorber (physical variable) & communicate this relationship to us through a graduated scale.

A generalized instrument is schematically represented as in Fig 1.1 below. It comprises of: -

1. A signal conditioner and transmitter
2. A transducer and
3. A recording/display device.



SIGNAL CONDITIONING TOGETHER WITH TRANSMITTER

The signal produced by a transmitter may require to be integrated, attenuated, amplified, modulated, differentiated, converted to digital signal etc. All these processes are known as signal conditioning. One or more of these functions are performed by the signal conditioner.

Since electrical signals possess advantages in this respect, given advances in electronics, a signal conditioner is now basically an electronic device.

Because of need for remote measurements, signal transmitters are necessary. Remote measurements and control is called telemetry, is a highly developed subject.

A potentiometer is an example of a signal conditioning device.

Recording Device/Display

It is needed to communicate information about the measurand to a person or to present it in an intelligent configuration.

CONTROL SYSTEMS

When variables such as flowrates, solar absorber temperature, turbine speed, heliostat focusing accuracy and CSP output power are monitored and measured, a control scheme or control system needs to be designed in order to ensure that all these variables are within permissible range. The variables mentioned above are all analog signals that may require an analog to digital (A to D) converter to be interfaced with a control computer or microcontroller and the control signals from a programmed computer needs again to be converted from digital to analog form for possible control of the said analog variables.

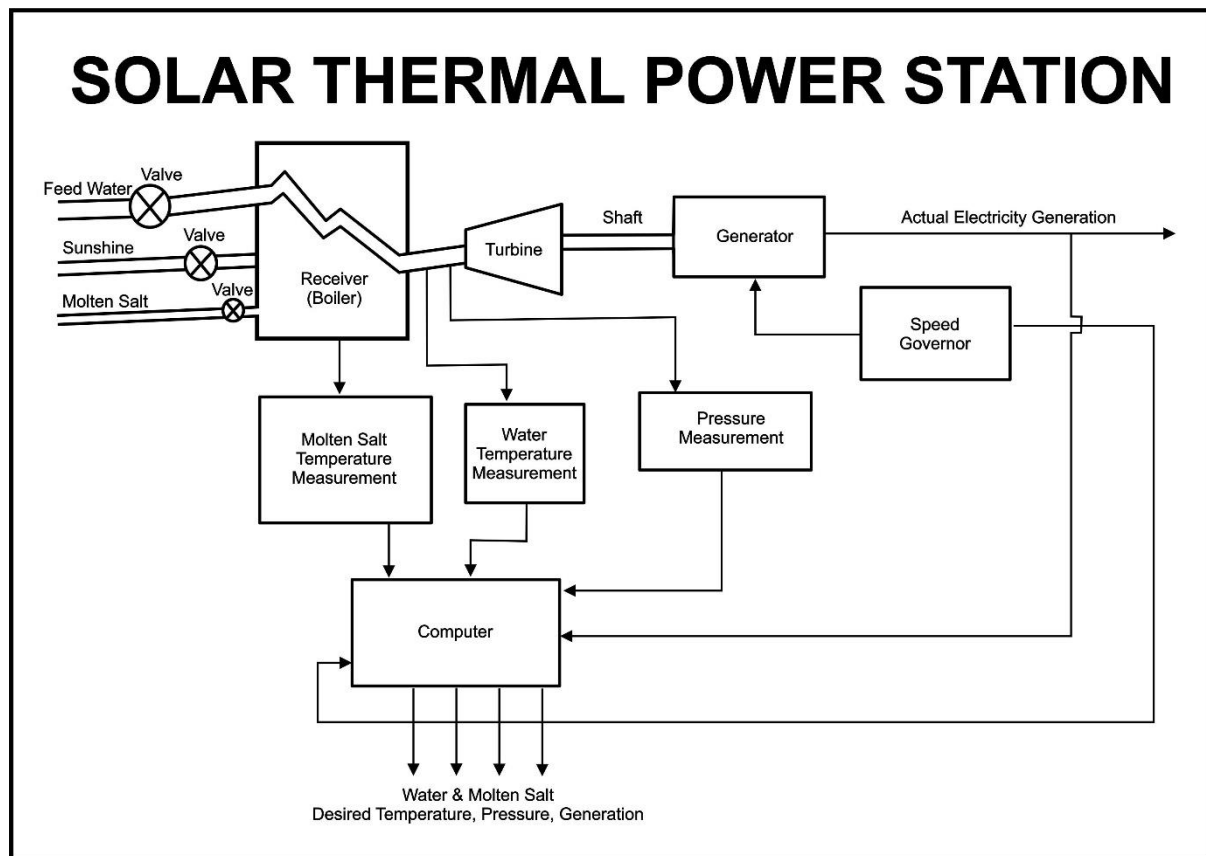


Figure 103

Above is a diagram for an automated CRT power station

Control systems can either be either classified as open loop or closed loop control systems. For automation of CSPs of the Central Receiver Type closed loop systems are imperative.

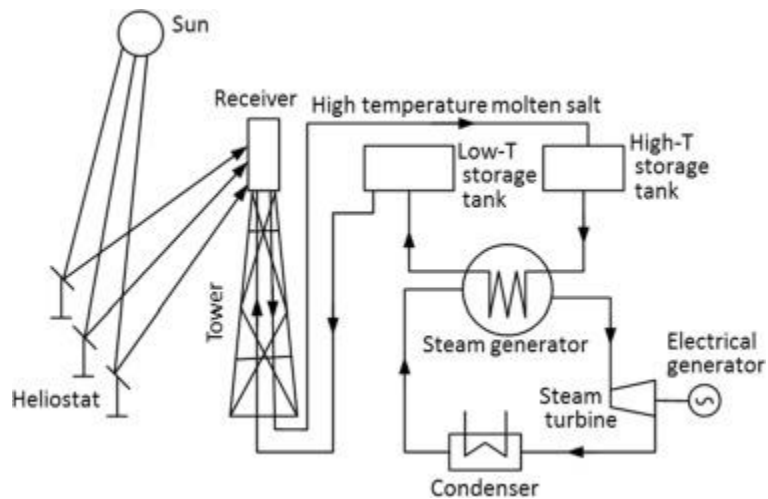


Figure 104

In Concentrated Solar Power the input is sunshine or solar insolation and the output is heat and the process is a mirror or mirrors’.

Solar insolation → Heat → Mechanical Energy (pressure) → Rotational kinetic energy → electricity.

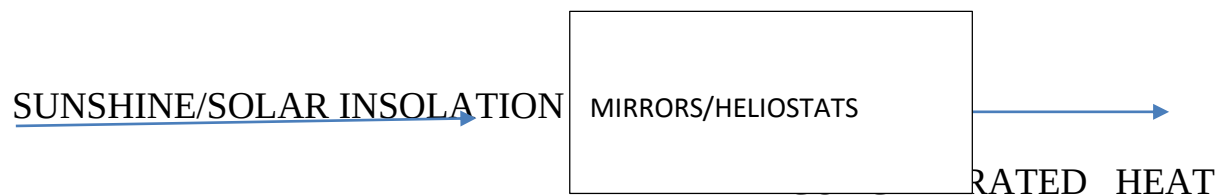


Figure 105

Or rather

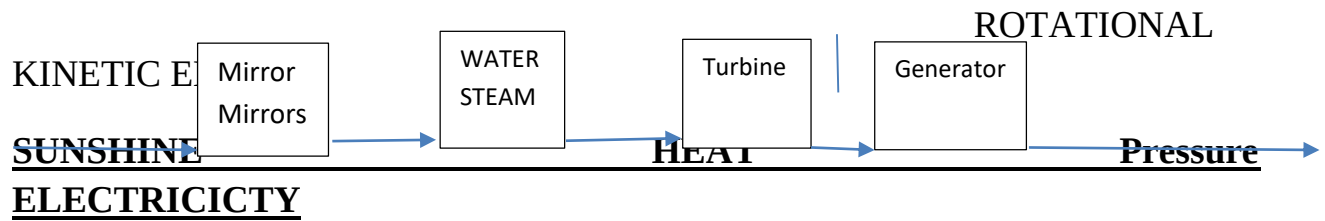
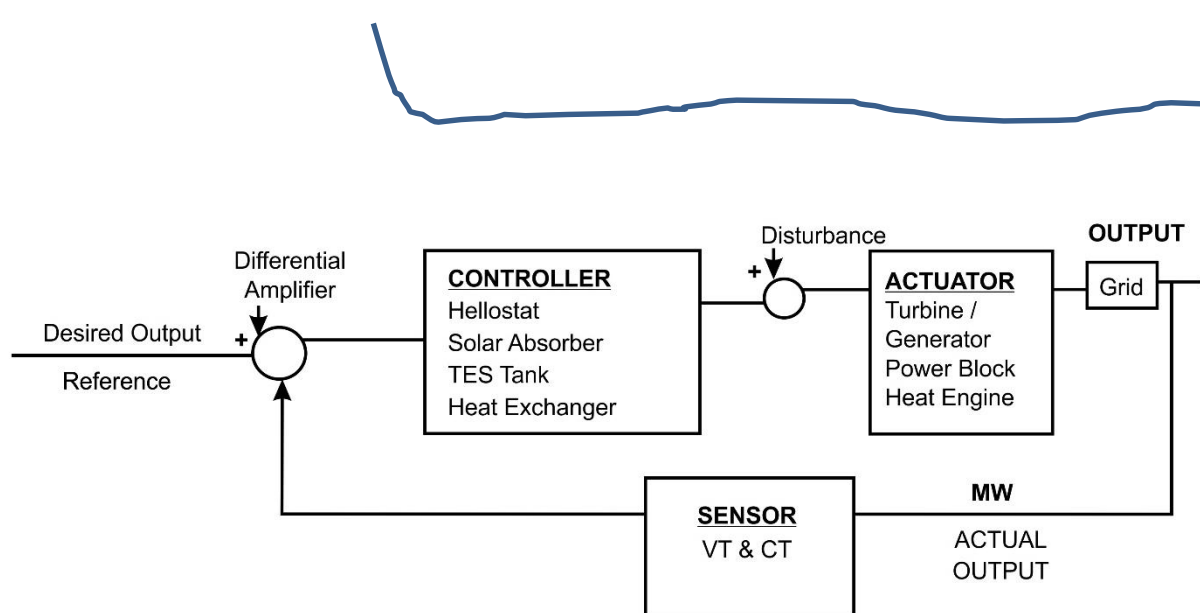


Figure 106



LEGEND

TES - Thermal Energy Storage Tanks
 VT - Voltage Transformer
 CT - Current Transformer
 MW - Megawatts

Figure 107

Local indications and measurements need to be wired in parallel with the National control centre. One gang two way switches need to be wired in control circuits with strappers connecting local and the National control centre for alternative control.

Conclusion

The paper concludes by recommending further studies in instrumentation, measurements, control, digital real-time telecommunications, Digital signal Processing, robotics, cloud computing, mechatronics in as far as they can improve functionality and the economics of operations of CSPs of Central Receiver Tower type. It further posits that advances in CSP designs and operational efficiency is inevitable in future because of the enough interest in CSPs of the Central Receiver Tower has generated.

The next Chapter is on the integration of solar generation with coal generation.

Chapter 4

4.0 The Integration of solar with Coal Generation in

Hybrid power Plants (HPP)

INTRODUCTION

This section explores how the 500 MW power plant can be integrated with existing coal power plants and discusses possible integration layouts. According to Serrano-Sanchez et.al. (2019), hybrids are meant to enhance operational stability of concentrated solar power plants whilst at the same time also reducing coal use of conventional coal plants. Proposed hybrids can emit 4.6 % less of pollutants due to solar energy use and reduce consumption of coal by the same amount (Serrano-Sanchez et.al., 2019). The levelized cost of electricity of the solar-coal hybrid power plants is found to be \$0.19/kWh according to Serrano-Sanchez (2019). Jin et.al (2021) posits that in solar-coal hybrids coal fuel can operating in the backup or boosting mode or fuel saving mode.

IEA Clean Coal Centre (2017) highlights the fact that in coal-solar hybrids, coal generation no longer operates for supplying base load, but used for load-following, regular start-stops become norm to compensate for fluctuating solar heating or generation.

While PV and wind are rapidly deployed in Southern Africa, their intermittency and lack of thermal inertia make them less suitable for hybridization with coal compared to solar technologies.

For separate free standing power plant to be successfully integrated to a coal powered grid there is need for: -

- (1) Synchronization to the grid using a synchroscope to ensure that the Central Receiver Tower Power Plant has the same frequency as the grid before integration.

(2) Phasing-in to ensure that the outgoing voltages of the Central Receiver Tower power plant are almost the same as the connection grid voltage.

Complications in solar-coal hybridization includes (1) introduction of grid instability (2) thermal mismatch which needs to be dealt with.

The section identified various configurations of integrated hybrid power plants e.g. two parallel operation and two series operation modes for integrated hybrids. The former has parallel but separate steam paths. The paths subsequently converge to result in a shared steam path to drive a turbine/generator set (herein called power block or heat engine) as a combined force which generates electricity in one parallel option. Another alternative identified is to have two independent solar and coal generation operating independent of each other but sharing the same site and grid connection. What differentiates an integrated hybrid and an independent hybrid is whether the two systems are joined together to be one just before or after the turbine/generator set. The section further investigates the possibility of hybrid generation for Munyati power station and Hwange power station in Zimbabwe. The advantages and disadvantages of hybrid generation are covered. It then gives advantages & disadvantages over pure solar generation and exclusive coal generation

The significance of the section is that it will broaden perspectives of how to integrate solar generation with coal generation or heating.

MAIN NARRATIVE

Adverse Impacts of Solar generation

1. The evening and day and also the sunny and cloud dynamics imposes solar flux fluctuations that results in variable generation in solar plants.
2. The fluctuations above results in problems of voltage instability.
3. The frequency of operation of FACTS technologies increases.
4. There is increased emissions and wear and tear resulting from the ramping up and down of e.g. coal power plants and other power stations

Mitigation Measures for Solar Generation

1. Energy storage systems
2. Hybridization with coal power plants
3. Automatic generation control (AGC) to enable the conventional generators to take compensatory action to varying solar generation. i.e integration with coal generation
4. Deployment of FACTS technologies
5. Increased power electronics and digital influence on the grid
6. Weather forecasting and therefore solar generation forecasting to enable the generation profile to be forecasted and plans to mitigate variability to be devised e.g spinning reserves. on the other nearby hydro and thermal power stations
7. Artificial intelligence and robotics as a corrective response solution to solar generation variability and uncertainty.
8. Microprocessor and grid intelligence solutions.
9. Neural networks solutions, machine vision, voice and sound recognition and learning from experience capabilities will prove handy on the medium to long term.

The integration of coal power plants with the 500 MW Central Receiver Tower Power Plant avails promising solution to the intermittence, installation cost reduction and greenhouse gas problems (Yousef et. al (2021) According to Yousef et al. (2021), it results in electric energy generation enhancement of 25 %. Zhu et. al (2017), says that the average annual CO₂ rate of emission of a hybrid system is diminished by 10.1 % compared to a standalone coal generation plant. According to Mills (2018), integrating coal with solar generation increases the working life of coal power plants and facilitates enhanced operational flexibility and plant costs can be reduced also. Mills (2018) posits that since solar is highly variable depending on weather, coal power plant or coal heating can act as backup when there is inadequate solar flux.

Yousef et al (2021) says that hybridization with coal power plants provides (1) reliability (2) more utilization of power generation equipment (3) flexible operation

(4) provides dispatchability (5) provides synergy Both Central Receiver Tower Power Plants and coal generation transform thermal or heat energy into electricity via the Rankine cycle. The other name for hybridization is complementation of coal generation with solar for energy production. Oxford Academy Clean Energy (2018) highlights that solar-coal hybridization increases flexibility of the power station whilst also diminishing CO₂ emissions and at the same time results in reduction of capital costs. The arrangement benefits from reliability and cost effectiveness of coal generation. Coal co-heating or coal co-generation results in less geographical space being required than in pure solar generation.

Yousef et.al. (2021) says that integration of Central Receiver Tower Power Plants(CRTPP) with coal can reduce the cost of generated electricity by between 20-30 % than standard CRTPP. There is less coal burnt and therefore less emissions than standalone coal generation. Yousef at al. (2021) says that integrated plant costs 72% of a CRTPP cost. The generated electricity can increase by 25% than a Central Receiver Tower Power Plant alone.

Advantages of a solar-coal Hybrid according to Ozfurt and Dincer (2018)

- Reduced maintenance and operation costs
- Reduced greenhouse gases
- Enhanced resource allocation
- Enhanced reliability
- Higher efficiency
- Diminished impact on environment compared to a pure coal power plant
- Reduces pollutants
- The consumption of coal is smaller compared to conventional coal power plants

According to Li et.al (2018) the solar-coal hybrid can operate in a fuel saving mode or power boosting mode. In fuel saving mode, the aggregate power output remains constant and coal use is reduced when there is availability of solar energy. In power boosting mode, extra power is generated and inputted coal remains constant when there is availability of solar flux.

Ozfurt and Dincer (2018), says that the energy efficiency of the combined system changes from between 19.43 – 46.05 % and the exergy efficiency of the hybrid system changes from 14.41 – 46.14 %. It has a maximum energy efficiency of 54.04 and maximum exergy efficiency of 57.72 %.

Problems That May Be Encountered in Integrating Power Tower Plants with Coal Powered grids

- Limitations of solar contribution.

Safety issues involving the boiler limits the quantity of solar power which can augment coal-fired power stations

- Complexity of operation

Presents difficulties in the allocation of output power of solar energy to coal powered grid

- Costs of Investment

Power tower power plants have greater investment costs compared to integrated units

- Load ratio possessed by the hybrid system

Integration Layout

This paper proposes ways in which solar heating or generation can be integrated into or with coal heating or generation in existing coal power stations like Munyati and Hwange power plants in Zimbabwe-i.e solar-coal hybrid power plants- mixed mode. The paper highlights that there are 4 coal power stations in Zimbabwe namely Harare, Bulawayo, Munyati and Hwange power stations. Harare and Bulawayo power stations have no land for integrating solar generation into existing coal plants, but Munyati and Hwange have ample land near them. The aim of the paper is to

design mechanisms of integrating solar heating or solar generation with coal heating or generation.

The paper highlights that solar-coal hybrid power plants have several advantages over solar only power plants or coal only power plants. There may be no pressing need for thermal energy storage. They are more reliable and cost effective. Greenhouse gas emissions will be reduced. This may act as a transitional step towards pure green generation or a transition from dominant coal generation to dominant renewable generation.

One obvious integration strategy is to have two independent coal and solar generation plants even separated by hundreds of kilometers but integrated in the grid by virtue of both supplies having the same frequency and at the same voltage level.

Enkhbayar et al (2021) highlights that thermal to electricity conversion efficiencies of hybrid power plants i.e. solar-coal are greater than those of solar only generation at the same temperature.

According to Enkhbayar, et al (2021), electricity consumption is increasing astronomically due to population growth, advancement in technology and economic growth resulting in increased climate change risks caused by dominant fossil fuel generation.

Mills (2018), posits that coal-solar pairing results in greater reliability and cost effectiveness and reduction in greenhouse gas emissions.

Fossil fuel generation accounted for 63.3 % of total electricity generation and caused 76 % of aggregate greenhouse gas emission as of 2021(Enkhbaya et al., 2021)). Solar

energy is associated with randomness and intermittency. Strategies to mitigate intermittency such as energy storage or hybridization are required. Solar-Coal hybridized Power generation (SCHPG) provides a compromise. SCHPG operates as a solar power station during sunny day and operates as a coal power plant during the night and also during cloud cover and can operate on dual or complimentary coal-solar complimentary heating or generation mode during the day. The coal-solar power plant can operate without need of an energy storage scheme. The plant can be constructed by modifying existing coal power stations like Munyati and Hwange power plants in Zimbabwe and the coal power station equipment could be exploited. Therefore, cost reductions can be realized. According to Enkhbayar (2021) the annual solar to electricity efficiency could reach values as high as 21%. The Enkhbayar (2021) says that, 'The levelized Cost of Electricity (LCOE) of a solar-coal hybrid power plant would reduce to 0.8 to 1.0yen/kWh which is about 20 to 30 % lower than the solar only thermal power plant'.

Coal generation is less costly than solar generation and solar-coal power plants strike a compromise of reducing greenhouse gases of purely coal power stations and cost considerations. Solar-coal hybridization brings in more efficiency. They are a co-located generation facility and reduce environmental footprint for coal generation. Both parallel steam heating facilities are joined together just before steam entry into the turbine blades for parallel operation or after. They will have either same turbine generator set or different for parallel operation. In series operation HTF is preheated by coal, then superheated by solar or the HTF is first preheated by solar, then superheated by coal in serial tubes.

An alternative is to allow thermal and solar generation to operate as independent units which share a site and some assets such as grid connection.

We substitute part of the coal generation with Central Receiver Tower power plant generation. In the other configuration part of the heat of the aggregate generation is obtained from solar and the other component from coal. The above reduces coal use and therefore reduces greenhouse gas emissions. According to Mills (2018), 'During

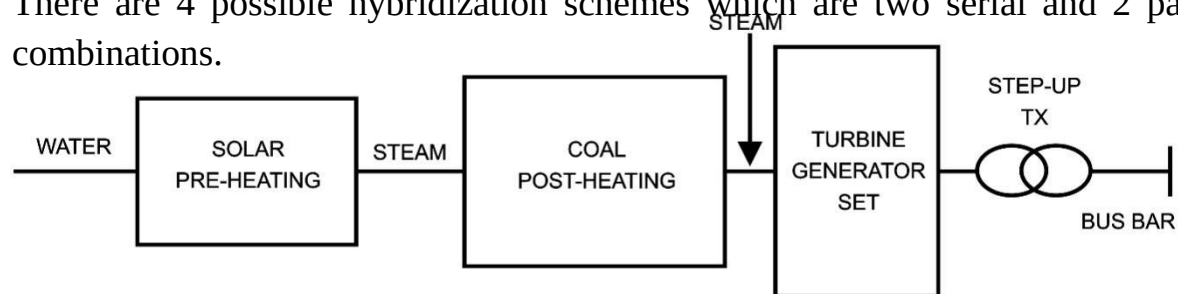
the day solar generation increases and coal generation diminishes. At night or during cloud cover coal generation increases.' This increases plant efficiency.

The solar collecting assemblage need to be located close to Munyati and Hwange power station. Solar heating has no mining and transportation costs unlike coal heating. Coal-solar Hybridization is one way of reducing greenhouse gas emissions and hence reduce climate change impacts associated with coal generation. It also improves the technical and economic performance of the overall plant. The front-end of a coal power station is split into 2 components solar & coal heating.

ADVANTAGES OF A SOLAR-COAL HYBRID POWER PLANT according to Hong etal (2014)

- The ability of operating the power plant at a full rated output power during periods of no or little solar irradiance e.g. during night or cloud cover.
- It reduces costs as it does not need energy storage as part of its architecture.
- It enables modification of coal power stations and therefore infrastructure such as at Munyati power station and Hwange power station can be utilized.

There are 4 possible hybridization schemes which are two serial and 2 parallel combinations.

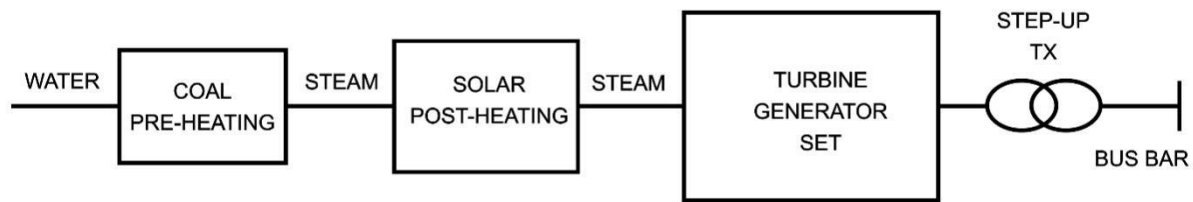


SOLAR PRE-HEAT & COAL POST-HEAT GENERATION

SERIAL COMBINATION WITH additional BYPASS FACILITIES FOR THE SECOND HEATING UNIT

Fig 1

In figure 1, solar heating initiates the heating process for the molten salt to about 250 to 300 °C which is later finished by coal heating to about 565 °C, the molten salt is then sent to a molten salt/water heat exchanger and directed to a turbine.



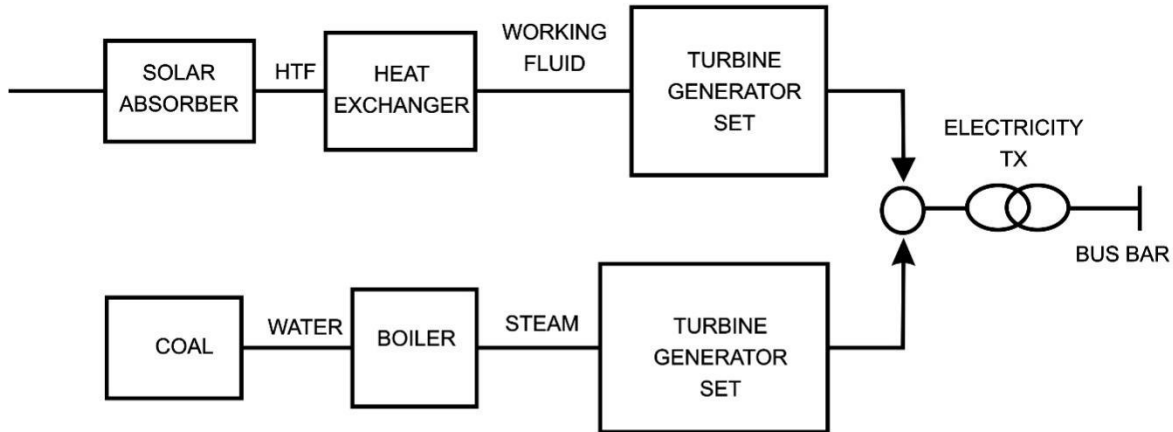
COAL PRE-HEAT & SOLAR POST-HEAT GENERATION

Fig 108

In Fig. 2 coal heating starts the molten salt heating process which is completed by solar heating. The molten salt is then sent to a molten salt/water heat exchanger and finally turbine for electricity generation.

PARALLEL COMBINATIONS

The integration can be before or pre-power block (turbine/generator set), just after or post-power block, after or post step-up transformer.



PARALLEL & SEPERATE STEAM & POWER BLOCK / HEAT ENGINE PATHS

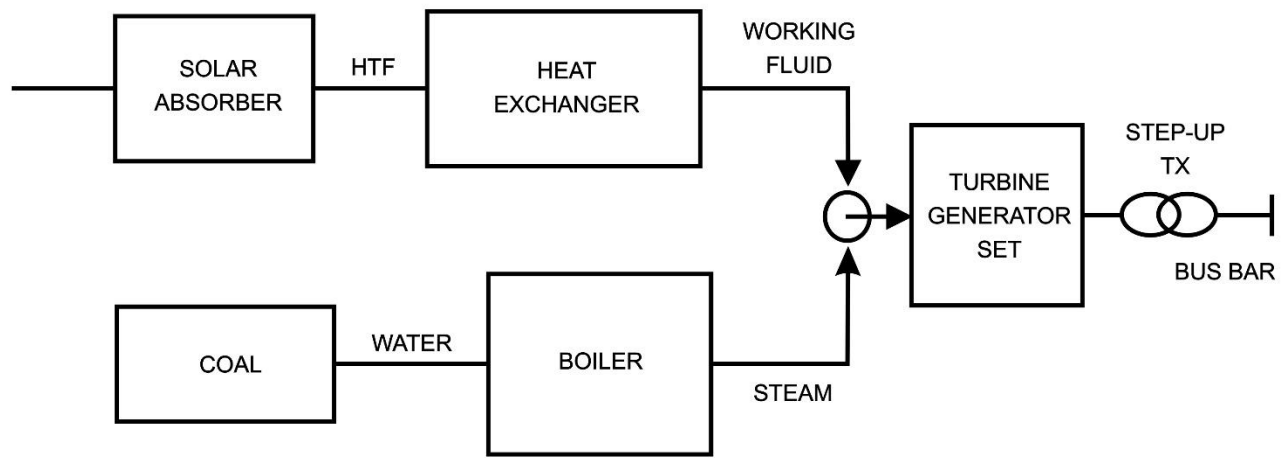
LEGEND

HTF - HEAT TRANSFER FLUID

TX - STEP UP TRANSFORMER 30/132 KV

Figure 109

Fig. 3 shows integration after the power block on the generation busbar. The diagram shows different steam and electricity generation paths. There is need for voltage phasing and frequency synchronization in this arrangement to ensure that the outputs from both arrangements match.



PARALLEL STREAM PATH WITH ONE HEAT ENGINE / POWER BLOCK

LEGEND

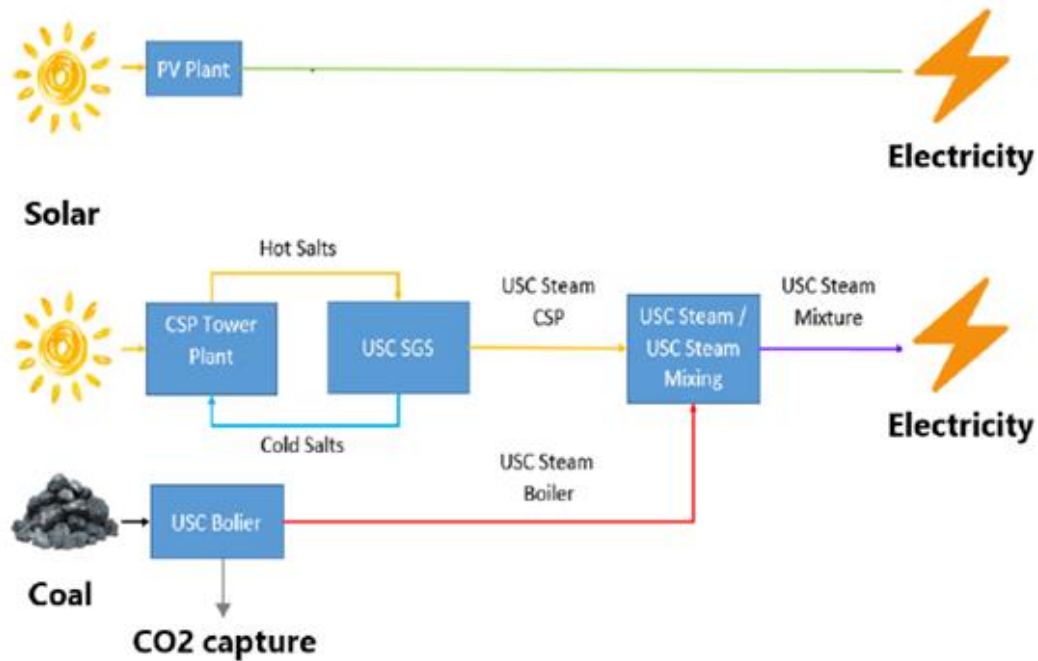
HTF - HEAT TRANSFER FLUID

TX - STEP UP TRANSFORMER 30/132 KV

Figure 110

Fig. 4 shows separate and different but later combined steam paths. The integration is just before the turbine/generator set. There is need for thermal matching in this arrangement.

The above combinations are made in such a way that the power station can operate as a pure coal power plant, pure solar power plant or as a coal-solar complimentary generation entity depending on weather imperatives and grid demands. Three modes of possible operation for each combination.



Picture of Munyati Power Station

Figure 111

Munyati power station consists of 5 Units with a total capacity of 100 MW. A project is currently planned to have a 100 MW Photovoltaic park near to site by ZPC. This paper proposes a third 100 MW Central Receiver Tower(CRT) Power plant to be

integrated with the coal power plant. The coal-PV-CRT tri-coupled power plant will bring flexibility, efficiency and cost-effectiveness as well as reduce greenhouse gas emissions from the plant as in Fig 3. There is need for phasing and synchronization of the two parallel schemes.

INTEGRATING MUNYATI POWER STATION WITH CONCENTRATED SOLAR POWER

The front end of coal power stations and solar power stations is different, but the backend is the same. It is proposed to replace the front end of coal heating at Munyati power station by solar heating i.e. to convert Munyati Power Coal Station to become a Central Receiver Tower Power Plant. This means the turbine generator set, the condenser, cooling tower, the Control building and step-up power station will remain intact whilst a Central tower, heliostat mirror field and heat exchanger will replace the boiler and coal bunker. The control room internal controls will need to be modified while the control building will remain intact.

Munyati power station has an original installed capacity of 120 MW but is normally operated at 100 MW. This means we have to design a heliostat field capable of outputting 120 MW of heat which needs to be converted to electricity.

If we assume the power station efficiency to be 20 %

20%=120 MW, What is 100 %

$\frac{100 \times 120}{20} = 600$ MW. The mirrors need to collect 600 MW of solar energy for the power station to output 120 MW at 20% efficiency.

Solar intensity levels at Munyati =500 W/m².

This means total area of heliostat mirrors required to generate 120 MW= $\frac{600\,000\,000}{500}=1\,200\,000\text{m}^2$

$$\pi r^2 = 1\,200\,000 \text{ m}^2$$

$$r^2 = 381\,818 \text{ m}^2, \quad r = 617.9 \text{ m}$$

$r = 617.9 \text{ m}$. If 10% of space is left to prevent shedding and blocking, total radius = $617.9 + 61.79$, $r = 679.69 \text{ m}$.

Therefore, we need a circle 680 m radius centred at the tower to generate 120 MW at Munyati power station, allowing 20 m for tower and other structures, the radius = 700 m radius.

Allowing $\tan \Theta = 0.24$, height of tower = 168 m high

Thermal Energy Storage Tanks

Density of potassium nitrate = $2\,110 \text{ kg/m}^3$

Density of sodium nitrate = $2\,260 \text{ kg/m}^3$

Average density with potassium nitrate to sodium nitrate being 3:2 = $2\,170 \text{ kg/m}^3$

Specific heat capacity of potassium nitrate = $1\,118 \text{ J/kg/K}$

Specific heat capacity of sodium nitrate = $1\,094 \text{ J/kg/K}$

Average specific heat capacity of a mixture of the two in above ratios = $1\,108 \text{ J/kg/K}$

Assuming the Energy storage tanks are 2 m high

$$Mc\Theta = 120 \text{ MW} = 120\,000\,000 \text{ W}$$

$$\text{Mass} = \text{density} \times \text{Volume} = 2\,170 \times \pi r^2$$

$$Mc\Theta = 2\,170 \times 10 \times \pi r^2 \times 1\,108 = 120\,000\,000$$

$r = 1.75 \text{ m}$ and height 10 m are the dimensions of the thermal energy storage tanks at Munyati

(b) The second option of integrating is to let the 500 MW designed Central Receiver Power Plant and the 120 MW Munyati coal power station feed on the same outgoing 11 KV or 30 KV outgoing busbar as long as the two power stations have the same frequency achieved through synchronization using a synchroscope and same output voltage achieved through phasing.

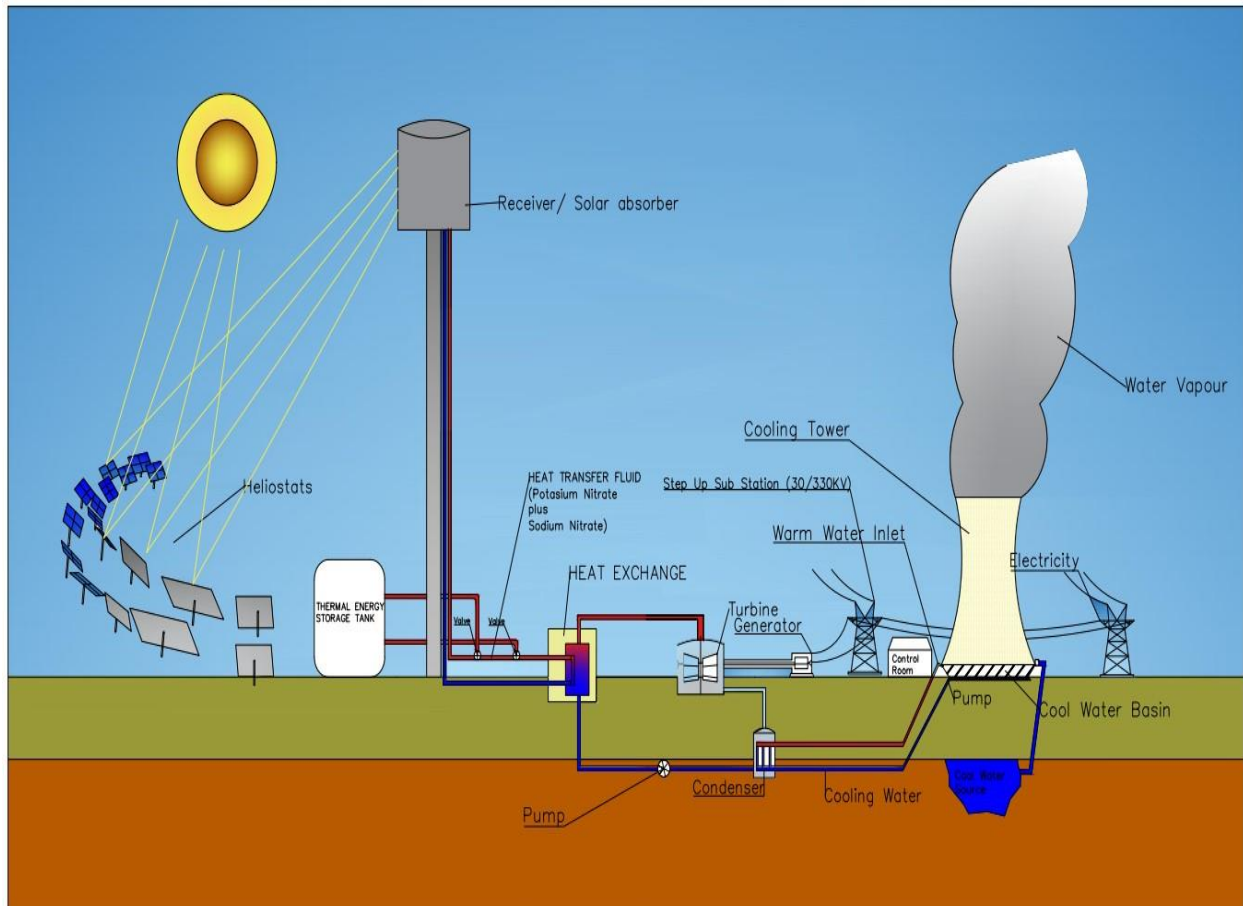
© The third option is to preheat the working fluid which is water with solar and post heat with coal or vice versa.

(d) the fourth option is to use the power station as a solar power plant during sunny clear skies and as a coal power plant during the night or cloud conditions rated at 120 MW.



Figure 112

COAL POWER PLANT TO BE CONVERTED TO BELOW POWER STATION



Central Receiver Tower Power Plant

Figure 113



Figure 114

HWANGE POWER STATION DETAILS

PROJECT DETAILS

<u>UNIT NAME</u>	<u>INSTALLED CAPACITY(MW)</u>	<u>STATUS</u>	<u>CURRENT FUEL</u>	<u>YEAR COMMISSIONED</u>
Unit 1	120	Operating	Coal	1984
Unit 2	120	Operating	COAL	1986
Unit 3	120	Operating	Coal	1985
Unit 4	120	Operating	Coal	1983
Unit 5	220	Operating	Coal	1986
Unit 6	220	Operating	Coal	1987
Unit 7	335	Operating	Coal	2023
Unit 8	335	Operating	Coal	2024
Unit 9	300	NOT YET BUILT	Proposed coal	-
Unit 10	300	“	Proposed coal	-
Unit 11	300	“	Proposed coal	-
Unit 12	300	“	Proposed coal	-
Unit 13	300	“	Proposed coal	-
Unit 14	300	“		-

TABLE 18

Unit1 to Unit 4 has a total installed capacity of 480 MW and can be replaced by the designed 500 MW Central Receiver Tower Power Plant in the same manner done to Munyati Power Station above.

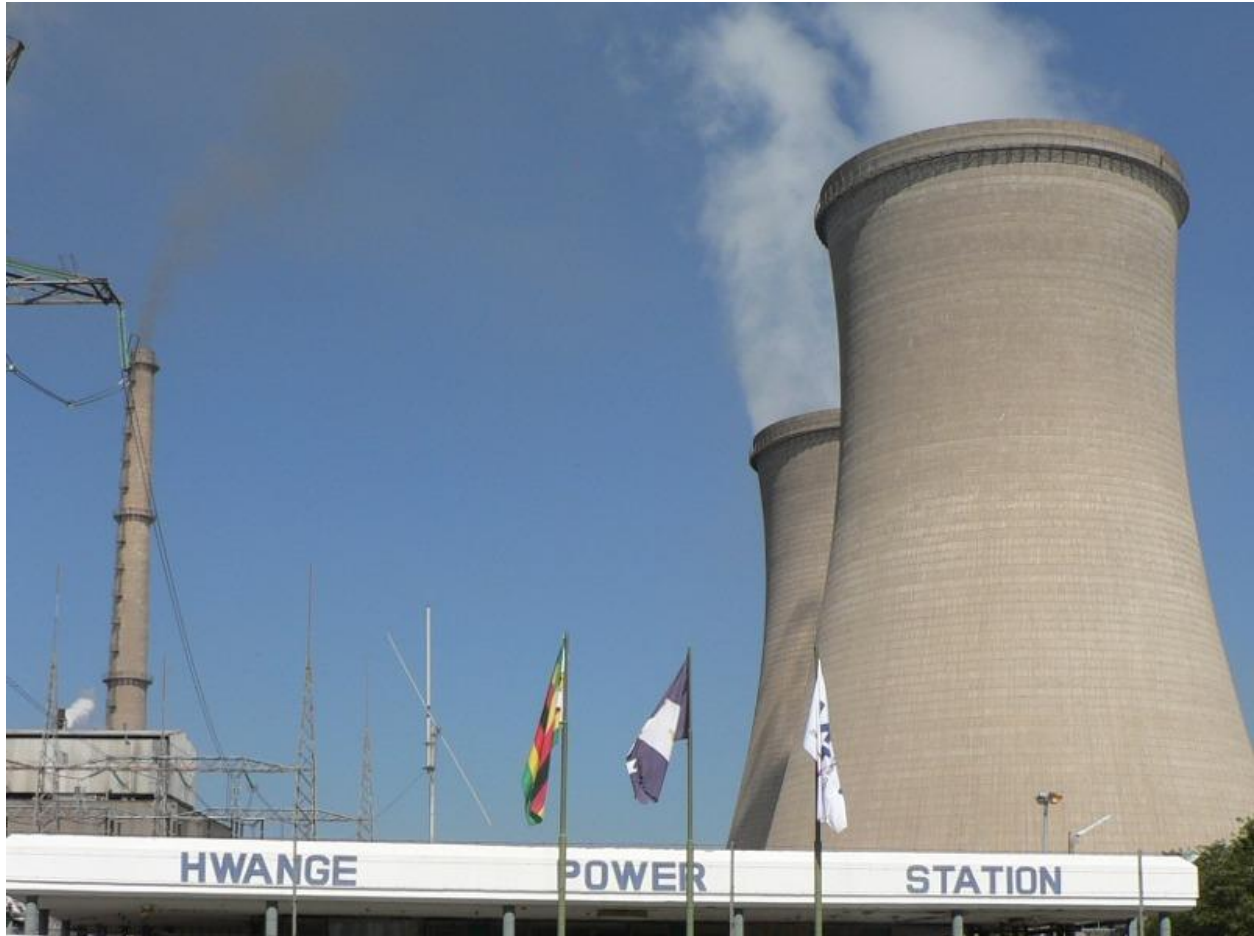


Photo Courtesy of NGAGE

Figure 115

Hwange power station has an installed capacity of 1 520 MW consisting of: -

- 4 units each rated at 120 MW each
- 2 units each rated at 220 MW each
- 2 units each rated at 300 MW each

It is proposed that a Central Receiver Power plant rated at 500 MW be paralleled with the 1 520 MW output of this power plant as in Fig 3. There is need for phasing and synchronization using a synchroscope.

The integration strategy proposed for Hwange power station is two separate and independent coal and CENTRAL Receiver Tower power plants feeding on the same 30 Kv outgoing busbar as long as the frequencies and voltages are the same.

CONVERTING HWANGE POWER STATION TO A CENTRAL RECEIVER TOWER POWER PLANT

If the average solar radiation at Hwange is taken to be 500 W/m², the calculations for the four 120 MW units' solar field and energy storage tanks is the same as that at Munyati Power Plant. The heliostat solar field is a circle with radius 700 m. The thermal energy storage tanks have radius 1.75m being 10m high

For the 220 MW units

20%=220 MW, 100 %=1 100 000 000

area of the heliostat mirrors= $\frac{1\ 100\ 000\ 000}{500}=2\ 200\ 000\text{m}^2$

If 10% of the area is for preventing blocking and shading, total area =2 200 000+220 000=2 420 000m²

$\pi r^2=2\ 420\ 000$, $r^2= 763\ 636\text{m}$, $r=874\text{m}$. Allowing 20 m radius for other structures $r=894\text{m}$

Tower height=0.24 x 894=215 m high

For thermal Energy Storage tanks

$r^2=5.3419$, $r=2.32\text{m}$ and 10m high

For 300MW units, area of heliostats, area of heliostat mirrors= $\frac{300\ 000\ 000}{500}=600\ 000$.

If 10% of area is for preventing blocking and shading, total area of heliostat field=660 000m²

$\pi r^2=660\ 000$, $r=459\text{m}$ is the radius of the solar field

For Thermal Energy Storage Tanks 10m high,

r of tank =2.7m high

HOW COAL-SOLAR INTEGRATION RESOLVES SOLAR INTERMITTENCY AND DISPATCHABILITY IN ZIMBABWE AND NEIGHBORING COUNTRIES

At night or during cloud cover, power generation from coal power plants is increased whilst during the day and clear skies generation from coal power stations is reduced i.e. ramping up and down of coal power plants. Thus coal power plants enable supply and demand match on the grid by complimenting shortfalls from solar generation when they arise. The instability caused by fluctuations in weather and therefore solar generation is minimized by the mentioned ramping up and down of coal power plants i.e. the increased or reduced coal generation.

The integration method where the designed power plant is several kilometers away from coal power plants, but feeding on the same Zimbabwean grid is the recommended integration style. The plant is for Kadoma several kilometers from Munyati coal power station, Harare coal power plant and Hwange power station.

SOLAR ONLY GENERATION	SOLAR-COAL HYBRID
Requires a lot of geographical space	Requires less geographical space because of coal contribution
Lack of continuity in electricity supply (Serrano-Sanchez et.al., 2019)	Continuous electricity supply because of coal input
Less flexible	Highly flexible
More costly	Less costly
Requires Heat energy storage	Thermal storage may not be necessary

Serrano-Sanchez et.al. (2019) says that solar generation is complex compared to coal generation. A solar-coal hybrid power plant benefits from each incorporated generation technology. The levelized cost of electrical power from a coal-solar

hybrid plant is found to be \$0.19/kwh and the exergy efficiency could be 35.8 % (Delgado and Petrakopoulou, 2019).

<u>COAL-ONLY GENERATION</u>	<u>SOLAR-COAL HYBRID</u>
Requires less geographical space	Requires more geographical space because of the solar heating or generation portion
More carbon dioxide emissions cause climate change	Less carbon dioxide emissions because of the solar heating or generation portion
Less costly	More costly
Less flexible	More flexible

Examples of Existing Solar-Coal Hybrids in the World

A solar-coal hybrid power plant exists in the USA which is called ‘the Cameo Project.’ Most hybrid power plants plans failed to come to fruition. In Australia 2 major plants were closed because of technical and contractual challenges (IEA Clean Coal Centre, 2017). New power plants are currently being developed in India and Chile. The Mejillones Power Plant in Chile will complement its output by incorporating solar energy. The Dadri power plant in India will employ solar energy to heat boiler feed-water, increasing plant efficiency and diminishing coal use. Coal-Solar hybrids are also under consideration in China, South Africa and Macedonia (IEA Clean Coal Centre, 2017).

Environmental Considerations

There are political, technical, environmental and financial challenges in implementing the hybridization of Munyati and Hwange power stations with the Central Receiver Tower Power Plant. The CRTPP require large tracts of land which could be used for farming and mining within the region. Farming and mining are the economic pillars of Zimbabwe, and Munyati is located in the Kadoma-Kwekwe mining region. According to Mills (2018), coal power plants need to be located near source of cooling water rarely sited in arid desert areas suitable for Solar generation. Fortunately for Munyati there is Munyati River. Every project is unique and it would be ideal to plan a separate solar-coal hybrid than modification of existing coal power stations like Munyati and Hwange. Although the emission of CO₂ is reduced due to the hybridization of coal power plants with solar Central Receiver Tower Power Plants, but there is still reduced emissions which poses climatic change challenges. The scenario is worse than 100 percent renewable generation.

POLICY BARRIERS TO COAL-SOLAR HYBRIDIZATION

- (1) At the moment there are just policies of scaling down or even shutting down coal generation rather than hybridization which becomes a policy barrier to hybridization
- (2) In hybridization schemes there will still be emissions of greenhouse gases which complicates convincing of policy makers to support coal-solar integration.
- (3) The force for total elimination of coal generation is strong among policy makers

KEY ASSUMPTIONS

1. For separate coal and solar power stations feeding onto the same grid, the frequencies are synchronized and voltages matched by phasing
2. For solar preheat-coal post heat and coal preheat and solar post heat there are thermal energy transfer fluid and working fluid bypass so that

the power station has capacity to also operate as a purely coal power plant and at times as a completely solar power plant.

The next discussion is on the summary of the design.

CHAPTER 5

PUBLISHED PAPER 1

4.1 Design of Heat Storage(HS) Schemes for Concentrated Solar Power Plants(CSPPs)

INTRODUCTION

Depletion of the ozone layer and climate change dynamics have resulted in the research and development of Concentrated Solar Power(CSP) plants that do not release greenhouse gases into the atmosphere. The sun is the source of sustainable, abundant and infinite renewable solar energy. The front end of the fossil fuel power plants is replaced in CSPs by solar heating, but the tried and tested backend of fossil fuels remains the same in the implementation of CSPs.

The sun only avails sunlight to earth for a maximum duration of approximately 10 hours daily of which there exist seasonal and daily (Diurnal) variations due to factors like humidity levels, rain and cloud cover. There is therefore need for thermal energy storage to attain 24 hours of electricity generation per day.

This portion of the thesis tries to provide a detailed, comprehensive and exhaustive review of the schemes that involve thermal energy storage schemes that are covered by literature (i.e. textbooks, journal papers and general google). The aim is to compare their economic benefits, highlight disadvantages and advantages of the various schemes of energy storage schemes. This section proceeds to size and dimension heat storage tanks for various heat storage schemes.

This portion of the project recommends tri-coupled energy storage schemes on a single CSP power station. e.g.

- (a) Sensible heat for night and day (diurnal storage or short term storage)
- (b) Latent heat for solar diurnal variability and cloud cover (medium term thermal energy storage) e.g. for weeks

(c) Thermochemical for long term seasonal variability (seasonal heat storage)- long term storage e.g. months.

all on a single power plant as an effective energy storage scheme! This section recommends the use of more, stronger and more resilient materials for energy storage tanks such as insulated carbon steel or stainless steel of appropriate thickness to prevent mechanical yield failures due to volumetric expansive forces induced by heat of the storage material therein contained in storage tanks. Engineering material sciences theory and experimental

evidence will assist in the design of storage tanks that has the capacity to withstand stress and tensile forces due to volumetric thermal expansion of storage material.

This technical section identifies thermal energy storage materials for the three storage technologies.

Keywords: Concentrated Solar Heat Power Plants(CSHPP), Latent Heat Storage(LHS), Sensible Heat Storage(SHS) and Thermochemical Heat Storage(THS).

1.0 MAIN NARRATIVE

Energy storage

The different forms that energy can be stored in include (1) kinetic and potential mechanical energy (2) batteries (electrical) (3) pumped hydro (4) heat or thermal energy (e.g. in CSPs storage (5) biomass (6) chemical reactants (e.g. nuclear) (Rao and Parulekar, 2009). Charged springs, compressed air and flywheel are also methods and techniques of storing energy as potential energy. The splitting of water into hydrogen and oxygen and subsequently storing hydrogen as a potential possible source of future energy. Since sodium nitrate and potassium nitrate mixed with suitable quantities of ammonium nitrate are used to manufacture gun powder, explosives and rocket fuel, these materials could also be employed as a source of stored energy.

Research into manganese and copper sulphate combined together with other materials need also to be researched on as a possible way of storing energy. The major and normally exploited storage schemes are thermal and electrical storage. It is difficult to store energy in the form of electrical in large amounts e.g. MWh range economically using conventional means. Other possible energy storage schemes are compressed air and pumped hydro, but these have to compete with alternatives such as expansion of generation, interconnectors with neighboring power utilities in other countries which does away with the requirement for storing energy. Thermal energy storage has been identified as an ideal energy storage scheme for Concentrated Solar Power(CSP) Plants.

Hot and Cold Systems

This system uses 2 storage tanks which are well insulated having essential piping, valves and pumps. The storage Heat Transfer Fluid is normally molten sodium salt or oil (R.K. Singal., 2016).

The tanks for storage are frequently constructed from austenitic stainless steel. Steel possesses a huge mechanical withstand strength value given likely forces that it may be exposed to during storage. Those forces could result from the volumetric expansion of the Heat Transfer Fluid.

The following table shows various materials, their melting points, boiling points and density which are critical dimensions used to determine storage tank materials and thermal energy storage materials including Heat Transfer Fluids.

Table 1.1.

Table showing Mechanical Strength of various materials for making storage tanks

MATERIAL	TENSILE STRENGTH(Megapascals MPa) Value	Sheer STRENGTH
1. Structural steel	400	210 000 Mpa
2. Carbon Steel	841	80 000 PSI
3. Ceramic materials	0.7 upto 7 000 MPa	17.35 UPTO 20.06 MPa
4. Diamond	20 GPa	85 GPa
5. Lithium	4 SI	43 MPa
6. Aluminum	90 MPa	55.2 MPa
7. Mild Steel	400 MPa	345 – 525 MPa

TABLE 19

Reliability, efficiency, cost and safety of the storage strategy have an outstanding influence on the selection and design of an energy conversion plant and storage subsystem (Rao and Parulekar., 2009)

Where thermal input exists like in Concentrated Solar Power(CSP) plants, enthalpy of the HTF through a heat exchanger to working fluid, heat engines or power blocks are employed to convert heat to electricity. Thermal energy storage is ideal in these technologies

The turnaround efficiency of electrical-thermal-electrical cycle is poor i.e. 20% to 30 %. With batteries as a storage tactic, we have electrical input, electrical storage and electrical output.

Storage cost per KWh, cost per KW and conversion efficiency become the most crucial economic factors that determine storage strategy choice.

In CSPs of the Solar Power Tower type, heat energy losses from the storage tanks and from the outside of the surfaces of flow-tubes need to be kept at a minimal, diminished and constrained using thermal insulators e.g. porcelain, fibre glass cement or asbestos e.t.c..

Toxic substances like Sulphur which have killed thousands of people before, depletion of the ozone layer, climate change considerations and coal dust that causes diseases like pneumoconiosis associated with the mining of coal have compelled experts in power system planning for power utilities to ponder about shifting from fossil fuels (oil, natural gas and coal) to renewables like wind and solar generation etc.

These renewables need to be coupled with energy storage technologies in order to make generation profiles smooth and hence electric energy supply profile of these highly intermittent, stochastic and variable renewables.

In electric energy generation techniques, renewables act as a status symbol of modernity among the electricity production mix injecting into the grid. Renewables play a decisive, significant and major role in guaranteeing environmental friendliness, sustainability and decarbonation and increasing security and efficiency in electricity supply.

Heat energy storage is a crucial process in the efficient and effective penetration of renewable energy in the electric energy production matrix in the global village because of the stochastic, intermittency, variability and randomness of many renewables like solar generation.

In an effort to balance variable load demand with stochastic generation, thermal energy storage technologies are not only vital, but indispensable for success in the supply-demand matching process.

Sunlight varies depending on night and day dynamics, diurnal (evening, morning and afternoon), seasonality and cloud cover incidents. It is also affected by factors like humidity and atmospheric temperature conditions. Such variability makes thermal energy storage schemes imperative, vital and necessary for generation flexibility and stability in the dispatch of power and load-following by the generating plant.

Heat energy storage helps in maintenance of solar absorbers and heliostat assembly without need for stopping electricity production in addition to enabling economic and competitive viability of CSPs.

High temperature application TES schemes operate in the temperature range of 200 °C to 1000 °C for example 565 °C for Solar Power Tower power plants. According to Palacios et.al. (2020), Heat Energy Storage Schemes enhance CSP installed capacity levels for electric power utilities. Guruprasad Alva et.al. (2018), says that Thermal Energy Storage technology also increase exploitation capabilities and energy management for power utilities. Sources of thermal energy include CSPs, nuclear and coal.

The sunlight-to-heat-to-electricity efficiency of conversion drives or affects the overall efficiency of a Concentrated Solar power plant. The solar absorber and the heliostat assembly helps in the transformation of sunlight to heat. Thermal energy storage tanks and technologies for heat storage, helps in the storage of heat in large amounts for exploitation when sunlight is not there or available. This smoothens the electricity supply curve to the grid and enhances capacity utilization of the CSP power plant and the grid i.e. guarantees continuity of supply.

The power block or heat engine helps in the transformation of thermal energy to electric power. Coupling CSPs with thermal energy storage schemes enhances flexibility in the grid operations. Energy could be stored in Thermal Energy Storage (TES) tanks during off peak for utilization during peak hours. Storage offers commercial profitability and flexibility emanating from higher efficiencies, increased capacity utilization of the grid components, supply adequacy and cost effectiveness resulting in customer delight amongst the power utility electricity consumers.

It is not possible to store electricity economically in large amounts appropriate for grid use e.g. in batteries and as a result electric energy has to be stored in alternative forms like heat energy, reversible endothermic reactions, pumped hydro and hydrogen atoms which could be simply later transformed into electricity when required.

Energy forms convertibility discovered many years ago has made life easier for the power industry e.g. sunlight –to-heat and heat-to-electricity using power blocks or heat engines.

Sunlight-to-heat-to-electric energy transformation technologies need to be designed encompassing thermal storage tanks as a superior, flexible and modern electric energy supply configuration.

The seasonal and diurnal variability of solar intensity levels poses challenges to power generation. The earth's position relative to the sun causes night and day variations in addition to cloud cover and humidity. This implies that the electricity dispatched from CSP power plants to the grid becomes variable, unreliable and unstable and as a result insecure without heat storage technologies.

Heat storage schemes for CSPs include (a) latent heat storage (b) sensible heat storage and (c) thermochemical heat storage technologies. Thermochemical heat storages involve reversible endothermic reactions. Alternatively, we could split water into oxygen and hydrogen and then store hydrogen as a source of energy. Other storage schemes include flywheels, charged springs, pumped hydro and compressed air.

According to Girolama et.al. (2020), sensible heat is the most widely used, abundant and frequently employed scheme among the 3 (i.e. sensible heat, latent heat and thermochemical heat storage). The reason for this is its (1) cheapness (2) reliability (3) simplicity of implementation (4) high historical feedback on experimental results and (5) the technology is past the 'learning curve'.

According to Achkari et.al. (2019), sensible thermal energy storage can be realized when a heat storage material (solid or liquid) undergoes a temperature variation

without undergoing through a chemical reaction or phase alteration e.g. sand, thermal oil or concrete.

According to Farulla et.al. (2000), sensible thermal storage schemes are based on the storing of heat energy which results in a linear temperature rise in a liquid or solid.

Sensible thermal energy stored=f(temperature change, mass of storage material, specific heat capacity of storage material).

According to Girolama (2000), it is highly desirable that materials for sensible heat possess good thermal conductivity, low carbon footprint, recyclability, high specific heat capacity (e.g. lithium), long term heat stability under cyclical stress and compatible with the container.

Fourier's Law gives the quantified amount of heat energy flow across a surface per unit area as follows: -

$$q = -k \Delta T = -k \left(\frac{i \partial T}{\partial x} + \frac{j \partial T}{\partial y} + \frac{k \partial T}{\partial z} \right) \dots$$

Where i, j and k are unit vectors in the x, y and z directions.

If the thermal flow is in a single or one direction, then

$$q = -k \frac{i \partial T}{\partial x}$$

The rate of thermal flow $Q = qA$

The equation will then translate to $Q = -kA\left(\frac{\partial T}{\partial x}\right)$

Note that Q is the total thermal energy flow past a point, q the thermal energy flow density and T is the temperature in degrees Celcius.

Heat flow maybe from the solar insolation to the solar absorber, from solar absorber to heat transfer fluid, from the heat transfer fluid to the heat exchanger and from the heat exchanger to water. (Asadi et al, 2018)

SENSIBLE HEAT STORAGE (SHS)

Some of the materials used in sensible heat storage include thermal oil, stone, sand and concrete. There is need to verify their states using the table below in comparison with the storage tank material's state and material used to make the receiver e.g. cermet or steel at normal operating temperatures of 565 °C upto 1000 °C. In this range, steel will be solid, sodium nitrate and potassium nitrate will be gases in this temperature range. Lithium will be liquid. Sodium will be liquid upto 882 °C and gas at temperatures exceeding 882 °C. It is not possible to operate the storage schemes at or above the melting point of steel which is used in the construction of the thermal energy storage tanks.

TABLE 2 PROPERTIES OF MATERIALS-SOME VALUES FROM TABLE BY WOLFRAM RESEARCH INSTITUTE & ALSO FROM REPORT BY METAL SUPERMARKETS (2020)

<u>POSSIBLE HEAT TRANSFER R FLUID MATERIAL L</u>	<u>MELTIN G POINT</u> (° C)	<u>BOILIN G POINT</u>	<u>DENSIT Y</u> (g/cm ³)	<u>THERMAL CONDUCTIVI TY(W/Mk)</u>	<u>COMMEN TS</u>
Silver	961	2 162	10.49	430	
Copper	1 084	2 562	8.96	400	
Gold	1 063	2 700	19.32	320	
Aluminum	660	2 470	2.7	235	
Calcium	842	1 484	1.56	200	
Beryllium	1 287	2 469		190	
Magnesium	650	1 091	1.738	160	
Silicon	1 410	2 355	2.32	150	
Carbon	3 550	4 815		140	
Sodium	97.79	882.8	2.26	140	
Stainless Steel	1 375- 1530	Non	7, 500 kg/m ³	15 W/K/m	
Carbon Steel	1 425- 1 540			45 W/K/m	
Lithium	180.5°C	1342 °C	0.534g/c m ³ as a solid	80 W/Mk	Lightest element of all solids
Liquid Potassium	63.5	758.8	0.862 g/cm ³	102.5 W(m-K	
Potassium Nitrate	334 °C	400 °C	2.11 grams per cm ³	0.62 W/K	
Diamond	700 °C	4 830 °C	3.5 g/cm ³	2 000 W/m-K	
Zinc	419.5 °C	907 °C	7.13 g/cm ³	112.2 W/m-K	
Asbestos	1 482 °C		0.36 g/cm ³	0.182 W/m-K	
Ceramic	2 000 °C		6 g/cm ³	1.10 W/m-K	
Concrete	900 °C		2.4 g/cm ³	2.25 W/m-K	

Sand	1 550 OC	2 230 OC	1 680 kg/m ³	2.05 W/m-K	
Silicon	1 420 OC	2 600 OC	2.329 g/cm ³	2.3 W/m-K	
Germanium	938 OC	2 833 OC	5.323 g/cm ³	1.45 W	
Quartz sand	1 650 OC	2 230 OC	2.65 g/cm ³	7.7 W/m-K	
Cement	1 550		1.44 g/cm ³	0.7 W/m-K	
Silica	1 200 OC		2.65 g/cm ³	1.31 W/m-K	
Granite	1 260 OC		2.65 g/cm ³	7 W/m-K	
Selenium	220 OC	688 OC	4.28 g/cm ³	2.04 W/m-K	
Uranium	1 132 OC	3 818 OC	19 g/cm ³	27 W/m-K	
Plutonium	639.4 OC	3 228 OC	19.84 g/cm ³	0.03 W/cm-K	
Chlorine	-101.5 OC	-34.04 OC	3.214 g/litre	0.00009 W/cm-K	
Fluorine	-219.8 OC	-188.1 OC	1.696 g/litre	0.0279 W/m-K	
Fibreglass	1 135 °C		2.44 g/cm ³	0.05 W/K m	
Porcelain	1 927 °C		2.4 g/cm ³	1.5 W/m K	
Polyvinyl chloride(PVC)	100-260 °C		40 kg/m ³	0.136 W/m K	
Expanded polystyrene	100 °C		1.05 g/cm ³	0.037 W/m K	
Polyurethane	44.1 OC	232 OC	30 kg/m ³	0.025 W/m K	
Alcohol	-114 OC	78.4 OC		0.481 W/m K	
Iron	1 538 OC	2 862 OC	7.87 g/cm ³	80 W/m K	

TABLE 20

The most abundantly and frequently used storage scheme in Concentrated Solar Power(CSP) plants is Sensible Heat storage. In thermal energy storage tanks, the quantity of energy stored via Sensible Heat is a function of (1) temperature change involved in the storage material (Θ) (2) specific heat capacity of the storage material (c) mass (m) of the storage material and is expressed through the following

Equation: -

$$Q=mc\Theta$$

Where m=mass of the storage material

C=specific heat capacity of the storage material

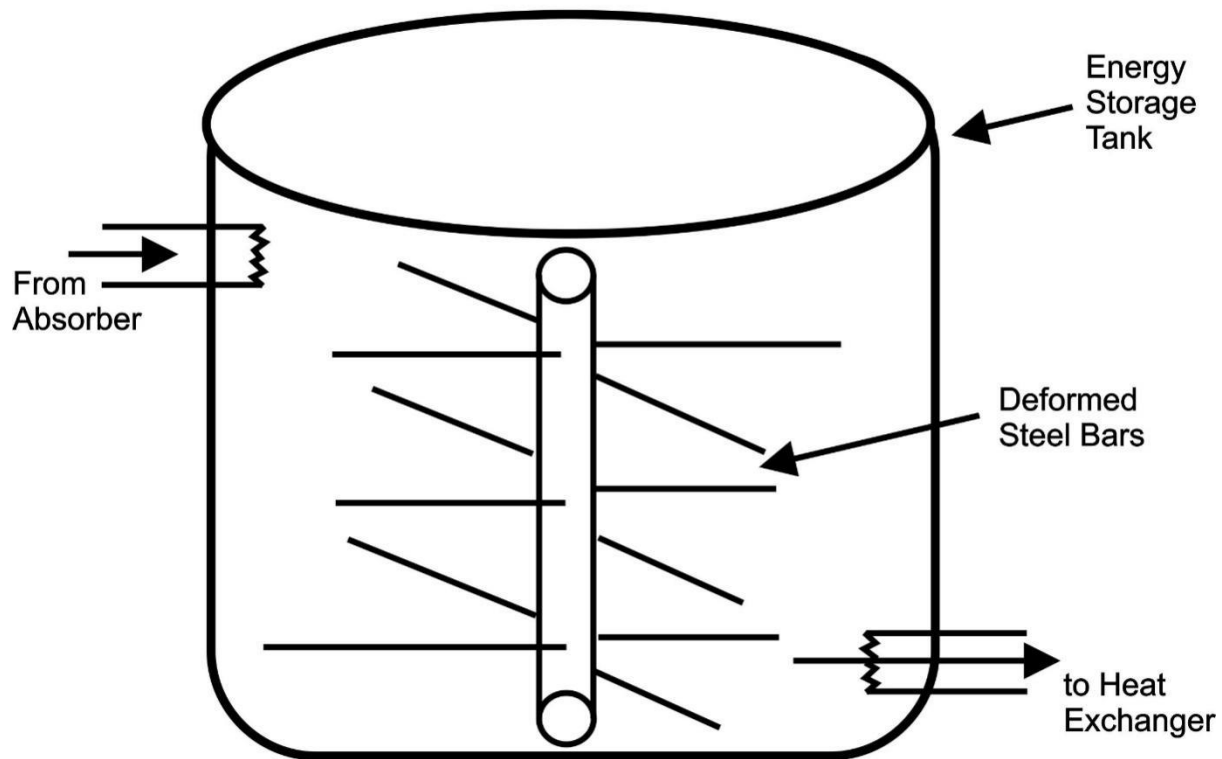
Θ =temperature change

According to Achkari et.al. (2019), 45.5 percent of all Concentrated Solar Power projects that are currently either under construction or are operational in the world (45.1 percent of the total capacity installed) are coupled with Thermal Energy Storage schemes. Ninety-five point six percent (95.6%) of them (i.e. 99.8 percent of the total capacity installed) use liquid Sensible Thermal Storage materials because of their low costs, operational simplicity and reliability. Thermal Energy Storage also diminish the levelized cost of electric energy.

Sensible Thermal Energy Storage is now a technology that is highly mature and widely used in CSP storage schemes and is almost past the ‘learning curve’ for power utilities.

EFFECTIVE HEAT DISTRIBUTION IN SOLIDS

e.g. Sand & Concrete Thermal Storage



Deformed steel bars help in uniform distribution of heat in solid and liquid sensible heat material which are bad conductors of heat e.g. sand, concrete and rocks (stones)

Figure 116

LATENT HEAT STORAGE(LHS)

Latent Thermal Energy Storage happens when thermal energy is absorbed at constant or same temperature while the material used for storage undergoes through a phase change usually from solid to liquid or vice versa.

According to Achkari et.al. (2019), Latent Heat Storage frequently allows higher heat densities than Sensible Heat Storage since the transfer of heat during change of

phase is frequently higher than the energy exchange that happens during the rise of temperature of a selected material. Sensible heat materials are potassium nitrate and sodium nitrate. Phase change materials are also inclusive of MgCl_2 , KCl , NaCl , NaCo_3 , KCO_3 and LiCO_3

PHASE CHANGE MATERIAL	MELTING POINT	LATENT HEAT OF LIQUIFICATION
Magnesium Chloride	714 OC	454 kJ/kg
Aluminum	660 OC	405 Kj/kg
Sodium Carbonate	851 OC	357.8 Kj/kg
Lithium Carbonate	723 OC	44.77 KJ/kg

TABLE 21

Latent heat storage is based on the principle of the storage of heat or thermal energy into storage material whilst it undergoes through a phase change simultaneously (e.g. solid to liquid or liquid to gas). In this technology, heat energy storage happens in the absence of a temperature change. The quantity of heat stored is obtained by multiplying the enthalpy change involved in the phase change process (melting or evaporating) and the mass of the storage material (J/kg).

Ice storage which is water dependent, or paraffin which is micro-encapsulated based on phase change materials are considered ideal for such applications (Girolama et al, (2020)).

Advantages of Latent Heat Storage include higher energy density compared to Sensible heat storage schemes (S. Kuravi et al., 2014).

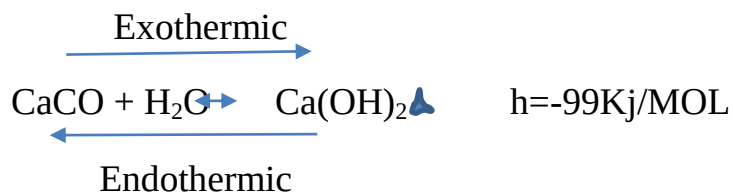
THERMOCHEMICAL HEAT ENERGY STORAGE (TCHEs) OR SORPTION

This scheme uses the reversible endothermic reaction principle which subsequently become exothermic on reversibility. Heat is absorbed and stored whilst the reaction is endothermic and energy is released during the exothermic reaction process. Speed of energy release and speed of energy absorption is determined by reaction kinetics. The reaction heat released during the reversible chemical absorption is recovered by Thermochemical Heat Energy Storage (Girolama et al,(2020).

Scapino et.al. (2015) says that in Thermochemical Heat Energy Storage the chemical reaction happens between a sorbate which is for example a vapor and a sorbent which is a liquid or solid typically.

As the charging process happens, a source of heat (e.g. sunlight) is used to start, invoke or kick-start an endothermic reaction. Sorbent and Sorbate are made to separate. Chemical or Physical energy contained in the two parts is stored separately.

During the exothermic reaction, the previously stored heat or thermal energy is emitted during the discharging process.



Latent heat storage involves the forming and breaking of secondary bonds whereas thermochemical heat storage involves the forming and breaking of primary bonds. Primary bonds are stronger than the secondary bonds (covalent bonds and ionic bonds) and have higher bonding energies.

Both latent heat and thermochemical heat storages have greater thermal or heat energy storage density and TES units which are modularized for intelligent control of temperature and higher operating temperatures. A 2-tank molten salt system involving both the hot tank and the cold tank is normally preferred for Solar Tower Power Plants which are also called Central Receiver Tower Power Plants.

The Thermal Energy Storage (TES) technologies facilitates the meeting of electricity demand 24/7 i.e. throughout the day and night and throughout the whole year hopefully and provided no maintenance is scheduled within the storage facilities.

There is continuous heat supply to the heat exchanger and as a result to the heat engine and the power block (i.e. both during the night and during the day, both during complete cloud cover and clear skies conditions. This increases capacity utilization of the Concentrated Solar Power (CSP) plant as well as the grid parts.

The Thermochemical Heat Storage technology is the last TES scheme that involves transforming heat into chemical energy e.g. when an endothermic reversible reaction absorbs and stores heat that may be for a long period of time without heat losses. This scheme has a large energy storage potential and a long period of storage. It has not yet been fully experimented and investigated on and as a result has not yet been fully integrated commercially in CSP power plants. More attention is being focused on Thermochemical Heat Storage schemes because of its performance which is superior compared to Sensible Heat Storages and Latent Heat Storages in terms of storage longevity or faster reaction dynamics and chemical kinetics during the discharging and charging and energy density (Cellura et.al. , 2020)

Theoretically, experimental as well as practically possible commercialization studies require to be enhanced in literature as part of contribution to the world body of knowledge.

Both thermochemical heat storages and sensible heat storages have high energy storage densities and are modularized.

Thermal energy storage schemes give additional flexibility, energy supply management capabilities, enhanced power supply quality and continuity of supply compensation for solar intermittency giving commercial profitability for CSPs (Concentrated Solar Power) Plants (Guarino et al. 2020).

During the period when there is excess generation, solar flux together with electric heaters transform solar heat and electric energy to heat in storage tanks using Sensible Heat, Latent heat and thermochemical heat storage schemes i.e. converting both excess electricity and excess solar flux into thermal energy stored in thermal energy storage tanks giving rise to future flexibility in supply and resulting system stability. Stored thermal energy is emitted when demand goes up and sunlight is low or not available. This gives rise to conservation of energy, load shifting and peak shaving and improved grid parts capacity utilization.

The thermal energy storage capacity of the tanks and storage materials is limited by the highest temperature of the condenser heat pump coupled to them.

Plenty of phase change materials (PCM), have low thermal conductivity that gives rise to slow discharging and charging rates.

APPLICATION AREAS OR USES OF THE STUDY OF REACTION DYNAMICS AND CHEMICAL KINETICS IN THERMOCHEMICAL HEAT STORAGE TECHNOLOGIES

In the optimization of the process of discharge and charge conditions in thermal energy storage materials we can use chemical kinetics. Kinetics may also be used to measure speeds of chemical changes during chemical and physical changes. When a chemical or physical reaction occurs 6 attributes may change namely color, smell, taste, heat content (enthalpy), mass and phase and texture giving rise to the 7 dimensions of chemical kinetics whose speed needs to be measured and quantified. The change in color is termed chromatic kinetics. The change in smell is termed Smellionic kinetics. The change in taste is called tastionic kinetics. The change in heat content is called enthalpic kinetics. The change in mass is called massionic kinetics and the change in phase is called Phaseonic kinetics. Finally, the change in texture or outside roughness is termed texturionic kinetics. The above nomenclature

is contribution to the World Body of Knowledge by the author. The rate change or chemical speed theories becomes exhaustive in their approach when analyzing chemical and physical changes in materials during chemical reactions involving thermal energy storage materials.

Sensible heat storage only experiences enthalpic kinetics. Latent heat mainly experience Phaseonic kinetics and thermochemical heat storage schemes may experience all the 7 dimensions' chemical kinetics.

The laws of physics and mathematics begin to apply in the chemistry of thermochemical, latent and sensible heat storage schemes.

The integration of physics and mathematics which are pure sciences in the chemistry of thermal energy storage schemes adds fun, exhilaration and excitement in the design of Solar Thermal Power Tower plants also called Central Receiver Tower Power Plants. Kinetics may also be employed in the analysis of chemical solutions and measurement of equilibrium constraints. The above offers the mathematical tools to fully explain changes in speeds and velocities of chemical reactions.

We may also exploit chemical kinetics in the analysis of the dynamics of interaction of solutes and solvents in thermal energy storage schemes of the Central Receiver Tower type.

TRIBRIDIZED OR TRICOUPLED THERMAL ENERGY STORAGE SCHEMES FOR CONCENTRATED SOLAR POWER PLANTS

These advanced heat storage schemes involve coupling sensible heat, thermochemical and latent heat storage tanks on one operational CSP plant and in the process harnessing all the advantages of these 3 collective schemes i.e. energy storage synergy through tri-coupling the storage schemes.

Hours to days' storage needs can be taken care of by Sensible Heat Storage. Weeks to months' storage needs will be addressed by latent heat storage facility while

seasonal to yearly storage needs will be satisfied by the thermochemical heat storage in that particular one CSP.

The tri-coupled thermal energy storage scheme removes most of the disadvantages of each individual storage scheme. They facilitate achievement of economies of scale, sharing storage stress. The discharging and charging cycles will be made longer and in the process minimizing tear and wear of the storage components resulting in improved life expectancy of the storage structure. Storage failure risk pooling will also be an added advantage. It is possible to service and maintain each storage scheme whilst production continues (preventive maintenance, fault maintenance, periodic maintenance, condition-based-maintenance and predictive maintenance strategies).

Maintenance may be done without total loss of storage benefits at any point as a function of time from the time the plant is commissioned.

IMPORTANT OPERATIONAL DIMENSIONS OR ATTRIBUTES OF HEAT ENERGY STORAGE(HES) SCHEMES (Ferulla et al., 2020)

- Storage span period: is the time that elapses from the time heat is stored and when no noticeable heat loss to the environment is recorded in the storage facility. No heat loss to compromise the operational and economic storage function
- The rate of discharging and charging: i.e. the response sensitivity and speed to energy demand by the grid or capabilities of load-following of the storage facility. This is a vital quality required for utilization of capacity of grid components, grid stability and superior service to electricity consumers.
- Capacity for Energy Storage: this is the aggregated and energy pinnacle that could be absorbed by a thermal energy storage facility while the activity of charging is proceeding under normal conditions without thermally, electrically or mechanically damaging the storage containers or any part of the CSP plant and also without posing hazards to utility members of the public and staff for example storage tank explosion.
- Thermal density, volumetric heat capacity or heat energy is defined as the ratio of the energy stored to the space volume of the heat energy storage facility.

- **Total Charge Time:** is the time duration that is needed to completely charge from zero. Total discharge time is the time duration that it takes to completely discharge from the highest charge to zero (0) of the energy contained in the storage unit.
- **Self-Discharge:** is the maximum amount of energy stored initially and dissipated or lost to the surroundings during a specific non-use period i.e. during the planned storage horizon.
- **Storage Efficiency:** is defined as the ratio of the heat enthalpy given to the grid from the thermal energy storage facility divided by the thermal energy needed to fully and completely charge the heat energy storage facility. This explains the heat energy lost to the surroundings while the storage is happening or during storage period and the discharge and charge cyclical span.
- **Storage Unit Response Time:** is the fastness or response rate sensitivity with which the heat energy is emitted, released or absorbed as a response to requirements of operational staff, grid demand, electric energy end-user needs or plant imperatives.
- **Discharge Cycle Frequency:** is the number of times the heat energy storage facility releases the energy following each recharge activity.
- **Cyclical life:** is defined as the period that the storage facility can discharge and charge without damage or before becoming non-functional due to tear and wear.
- **Total Costs of Storage Unit:** is defined as maintenance costs plus operational costs plus capital costs during its operational life expectance.
- **Cost Per Usable Heat Energy Output:** is defined as the ratio of the cost for one unit of energy divided by the storage efficiency.
- **Cycle Cost:** is defined as the involved cost per unit heat energy divided by the number of discharge/charge cycles involved.

THERMAL ENERGY STORAGE SCHEMES CLASSIFICATION

The time span period of valuable heat energy storage is used to classify thermal energy storage schemes.

Long-term Storage: This is where the discharge/charge happens within seasons or even years for example Thermochemical heat energy storage has minimal or no self-discharge and is a type of long term storage.

Medium term Storage: This is whereby the discharge and charge process happens within weeks or months. Latent heat storage is a type of medium term storage.

Short term Storage: This is whereby thermal energy output and input (discharge/charge) occurs within a number of hours or days. For example Sensible heat storage is a type of short term storage (Cellura et.al. , 2020)

Insulation of containers is needed during the time of heat storage for latent heat and sensible heat storage in order to prevent heat losses. They have the disadvantage that they cannot store heat for long periods.

Thermochemical heat storage facilitates the possession of higher storage densities of 5 to 10 times in comparison with latent heat storage systems and sensible heat storage schemes respectively.

Thermochemical heat storage schemes are as a result experiencing much research effort because of its advantages. Because of higher energy storage densities, thermochemical heat storage schemes are compact and in the process reduce the volume space requirements of the heat storage facility.

If there are constraints of space, thermochemical heat storage schemes are the ideal candidate for coupling with CSPs.

Sensible heat storage schemes cost less than thermochemical heat storage or latent heat storages. Upfront high capital costs are the major hindrance to extensive deployment of thermochemical heat storage facilities in the whole global village.

In CSP power plants, during the commissioning stage, the thermochemical heat storage kick-starts the process by being initially charged to the maximum, and subsequently the latent heat storage is charged to the maximum and lastly the sensible heat storage is charged to the maximum and then the Central Receiver Tower Power plant is put into full electric power production activity and electricity supply service.

Molten salt i.e. potassium nitrate and sodium nitrate is frequently used as heat transfer fluid in order to capture and transmit heat from the solar absorber for transporting thermal energy to heat storage tanks or to heat exchangers for direct power generation in the turbines (Zhang et al (2024)). For operations involving startups, molten salt requires to be pumped so as to flow within the pipes that may have lower temperatures than the melting point or freezing point of molten salt (334 °C for potassium nitrate and 308 °C for sodium nitrate) along cold pipes turns to be a crucial issue to the safe operation of Central Receiver Tower power plants or Concentrated Solar Power Plants in general.

Flow velocity and heat capacities of molten salt affect the location of the onset of freezing of the molten salt (Zhang et al. (2024)). For safe operation the overall operating temperature must not fall below 340 °C. Since average temperature in the solar absorber is 565 °C the temperature must not fall below 410 °C for both salts to remain gaseous and never below 340 °C to avoid freezing inside pipes.

THERMOCHEMICAL PROCESSES AND HEAT ENERGY STORAGE MATERIALS

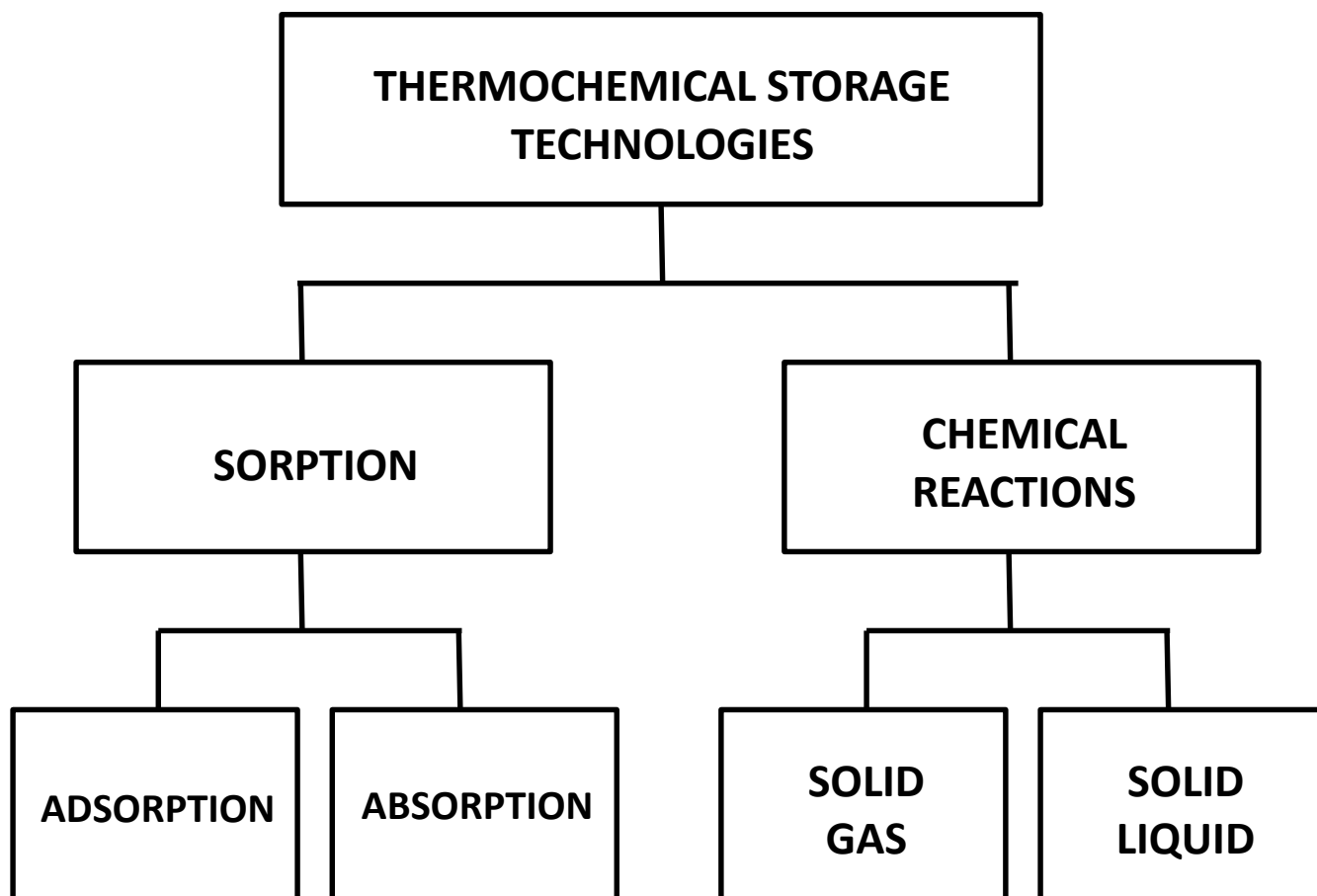


Figure 117 Thermochemical Heat Storage principles-classification from a paper by Girolama et al (2020)

Thermochemical reactions fall into 2 classes namely (1) sorption (adsorption and absorption) and (2) reversible chemical reactions. Chemical reactions (solid to liquid or liquid to gas) are categorized based on changes involving configuration of molecules in chemical compounds involved. According to Tu et.al. (2014), both sorption and reversible chemical reactions are included in the sorption definition.

We define desorption as the process of charging during which heat energy offered to the storage elements or compounds is archived in the form of potential chemical energy by undoing or dismantling of the bonds between the sorbent and sorbate.

We define storage as the process where the sorbent and sorbate are made to separate.

We define sorption as the process of discharging directed at recovering heat energy by ensuring the bringing together of the sorbent and the sorbate.

We define sorption as the activity of trapping or fixating of a gas or vapor by a substance that condensed.

According to Nic et.al. (2015), adsorption is the process or activity that involves the retention of adsorbate by the absorbent.

According to Yu et.al. (2014), the process that happens at the junction of 2 phases where the forces of cohesion reacts or behave with the molecules of all substances without regard to their aggregation state is called adsorption.

Often sorption materials are regarded as composite sorbents, solid and liquid e.g. the following: -

- H_2O /LiBr solution
- H_2O /LiCl solution
- activated alumina/LiCl
- expanded graphite/LiCl
- H_2O /LiCl₂ solution
- H_2O /CaCl₂ solution
- Binary sales
- Zeolite 5A, Zeolite 13X, Zeolite 4A
- silico-aluminophosphates (SAPO_5) and Aluminophosphates(AlPO_5) and
- Composite materials manufactured by combining an additive and a salt hydrate having high heat energy conductivity and a porous structure (expanded graphite) activated carbon, carbon fibre and metal foam (Farulla et al., 2020).

(SAPO_3) and (AlPO_5) are included among materials that are promising of sorption that could be exploited for low temperature heat storage.

Zeolite 13X is the most highly researched on material used in thermochemical heat storage because of its hydrothermal and mechanical stability and non-corrosive nature.

$\text{MgSO}_4\text{-MgCl}_2\text{-H}_2\text{O}$, $\text{LiBr-silica gel/H}_2\text{O}$, $\text{CaCl}_2\text{-silica gel/H}_2\text{O}$, $\text{CaCl}_2\text{-FeKII}_2\text{/H}_2\text{O}$, , $\text{MgSO}_4\text{-Zeolite/H}_2\text{O}$, are examples of composite materials..

Heat (e.g. 100 to 400°C) and higher (greater than 400°C) can be stored in chemical reactions. Below are examples of chemical reactions: -

- Deammoniation of ammonium chlorides
- Dehydration of metal hydrides
- Dehydration of metal hydroxides
- Dehydration of salt hydrates
- Metal oxide redox
- Catalytic dissociation
- Methane steam reforming
- Decarboxylation of metal carbonates

(Cerulla et al., 2020)

Many studies of MgO hydration were done as far back as 1960. Ca(OH)_2 's hydration was exposed to wide attention as early as 1988.

CaO/Ca(OH)_2 's investigations as a heat storage material was supported by the American Pacific Northwest National Laboratories and the National Energy Administration.

$\text{Ca(OH)}_2/\text{CaO}$ systems are often used by chemical processes and has many advantages e.g. (a) high reaction enthalpy (b) reaction kinetics which are efficient.

They are widely exploited valuable materials in thermal energy storage specifically for systems with high temperatures (400-600 °C) in plants in industry.

Thermochemical heat storage facilities using $\text{Ca(OH)}_2/\text{CaO}$ in thermal-to-power applications has caused high research effort with focus on the thermal and mass transfer processes.

Thermochemical storage schemes using metal hydrides were researched on since mid-1970s. Schemes based on Mg are giving hope of successful results among all metal hydrides emanating from their high reaction enthalpy. Schemes based on Mg exhibit cyclic stability (from 250°C to 550°C) with high heat densities of energy coming upto 2 257KJ/KG. Metal hydrides have good cyclical stability combined with high enthalpies and reversibility.

Hydrates of salts have high temperatures and energy density of desorption that enables them to be ideal for employment in heat-to-power schemes and waste heat sources. Many advantages are shown by carbonates of metals e.g. abundantly available, high energy density, non-toxicity and low cost. Such advantages make carbonates of metals suitable for thermochemical heat storage uses.

Other materials include CaO/CaCO_3 (having a density of 0.49 kWh/kg). CaCO_3 is one of the most highly available material within nature.

According to Fernandez et.al. (2012), CaO/CaCO_3 was used as the working pair so as to form a system called ‘Photovoltaic Calcium Looping (PV-Cal)’ to build a big heat thermal energy storage scheme.

There was demonstration by this pair that high turning temperature of the carbonate which was an exothermic reaction allows the employment of high efficient power cycles.

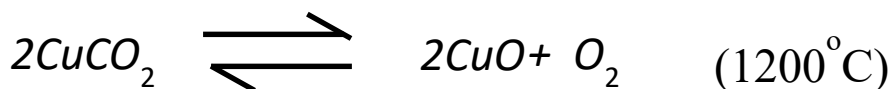
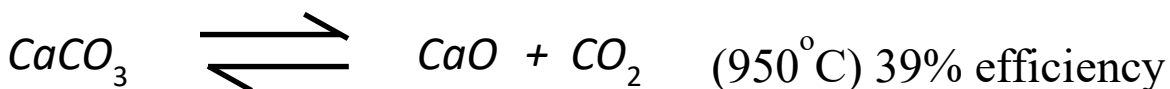
Thermal storage facilities require excellent thermal transfer and high thermal storage capacity to do their functions well.

There is closed loop and open loop thermal storage schemes of the thermochemical type.

Closed loop systems function with water vapor or steam doing rounds in hermetically closed loops in the presence of pressure vacuum. Open loop systems function exposed to the pressure of the atmosphere and are invariably in interface with the outside surroundings.

An open loop scheme is easier in its design.

Reversible Reactions



The increase in demand of energy from the electricity grid initiates the discharge process. This period starts the exothermic process that gives additional heat for the power block and as a result more electric power is injected into the grid.

Within this exothermic reaction, the molten CuO_2 / CuO stored is subsequently oxidized and its thermal level is reduced into an oxidation reactor using air.

Thermal storage density is the heat energy per unit mass of the raw material of CuO .

We define the round trip efficiency as the quantity of electric energy that could be recovered per given energy input.

The major disadvantage for the above methodology is huge heat sources, elevated operating temperatures, maintenance costs, high operational costs, high investment costs, complexity and high operating temperatures.

$\text{NH}_3/\text{LiNO}_3$ in which LiNO_3 is the sorbent and NH_3 is the solute.

REACTION DYNAMICS AND CHEMICAL KINETICS IN THERMOCHEMICAL HEAT STORAGE

According to Connors (1990), the study of Chemistry can be broken down into 3 main areas of study namely (1) equilibria (2) structures and (3) rates or speed of chemical reactions.

Techniques of quantum mechanics explain the chemical structure of a molecule or an atom of a substance.

Statistical mechanics facilitates the study of equilibrium and the study of rates or speed of chemical reactions which constitute kinetics is facilitated by thermodynamics.

Kinetics is the study of the measurement, interpretation and quantification of the rates or speed of chemical reactions. It is vital to choose thermochemical heat storage reactants or materials having a high rate or speed of reaction so as to achieve fast discharge and fast charge and therefore quick response to demands by the grid of the Central Receiver Tower Power plant. When the storage reactants or materials are absorbing or receiving thermal energy i.e. endothermic, we say it is charging. When the storage reactants or material emit or releases thermal energy to the heat engine, we say its discharging.

We can divide kinetics into 2 main categories namely (1) chemical kinetics and (2) physical kinetics (Houston, 2000). Chemical kinetics encompass the rates or speeds of reactions (involving non-covalent and covalent bond changes) (Connors, 1990). Physical kinetics embrace phenomena which is physical for example viscosity and diffusion.

The study of thermodynamics in thermal energy storage facilities e.g. in storage tanks and receivers of thermochemical heat storage facilities is restricted only to the analysis of the final state and the initial state of the reactants of the system after reaching equilibrium.

The intermediate stage of intervening processes that is overlooked by thermodynamic analysis is the focus of chemical kinetics. What happens between the initial state and the final state of a chemical reaction and exactly how fast and how the transition from one given state to another given state happens in the realm of chemical kinetics.

In thermochemical heat storage we use reversible endothermic reactions which will become exothermic on reversibility. Reactions which absorb heat in one directions and releases heat in the reverse direction.

Enthalpy restricts the specific heat capacities of various heat storage materials which is of vital importance in the design of Central Receiver Tower Power Plants heat storage schemes.

Kinetics makes effort to explain the dynamics of behavior involving molecules during the process of collisions of these molecules and the subsequent conversion to new species and move apart or separate again.

Alterations in quantities of thermodynamics like entropy and enthalpy depend on final and initial state of the thermochemical heat storage materials or reactants.

Thermodynamics is limited by the fact that it doesn't offer vital, critical and essential information regarding intervening states of the heat energy storage materials in storage tanks and receiver or HTF transport pipes.

It is definitely, precisely and exactly these intervening and intermediate stages that becomes the realm and subject matter of chemical kinetics that is a highly exciting subject and focus of study in heat storage schemes of the Solar Power Tower power plants with thermochemical heat storage schemes.

Any comprehensive, exhaustive and thorough study of chemical reactions involved in thermochemical heat storage schemes should fully cover (1) kinetic research, investigation and analysis (2) structural analysis (3) equilibrium.

Any system in equilibrium's chemical properties do not change with time and as a result is not a thermodynamic variable. Any free, unconstrained and unrestricted system that is not in equilibrium state changes spontaneously with time and experimental and theoretical studies of such changes involve time and time becomes a variable that must be accounted for and a variable of interest in chemical kinetics.

A chemical reaction's speed is a scalar quantity in physics. This project contributes to the, 'World Body of Knowledge' by introducing the 8 dimensions or variables of and in chemical kinetics (color, taste, smell, enthalpy, phase, texture, mass, sound) which are properties that may change when a phase change or chemical reaction like in latent heat storage or thermochemical occurs. We need to be able to accurately measure the speed of such reactions and hence the following contribution. The author also coins the nomenclature chromatic kinetics(speed of color change), tastionic kinetics (speed of change in taste), Smellionic kinetics (speed in change in smell), enthalpic kinetics (speed in the rate of change of heat content), Phaseonic kinetics(speed the rate of change phase change in latent heat storages), massionic kinetics(change in mass), texturionic kinetics(change in outside texture) and soundiotic kinetics(change in sound when hit by an iron object such as a spoon) The project also introduces the concept of the velocity of a chemical reaction which is a vector variable and takes care of quantity(i.e. numerical speed) as well as direction of the change.

Contribution to World Body Of Knowledge on Color Change Spectrum/ Range or Scale

Colorless=0, white=1, Cream=2, Yellow=3, Orange=4, Pink=5, Red=6, Brown=7, Purple=8, Green=9, Grey=10, Black=11

Whitening Direction or Darkening Direction to make it a vector quantity in addition to numerical quantity calculated from above numbers

Taste Spectrum / Range

Tasteless=0, Sweet=1 , Sour=2, Bitter=3, Toxic poison taste=4

Tasteful direction or bitterness direction

Smell Spectrum

Smell-less=0, Sweet scent=1, bad smell=2, Odorous=3, Stinking=4 Poisonous smell=5

Phase Change Spectrum

Solid=1, liquid=2, Gas=3. The possible physical forms that matter can assume is called 'states or phases of matter'.

Literature says there are 3 states of matter as highlighted above, but this author would like to expand the phases into 6 states by expanding the solid state into 3 major states (a) rock-solid (b) powder and (c) paste, so the phase Spectrum will be as follows: -

Rock-solid=1, Powder=2, Paste=3, liquid=4 and gas=5, plasma=6

Phase change direction- gasification direction (from left to right) or solidifying direction (from right to left). Which makes it a vector. If direction of phase change is ignored it becomes a numerical scalar quantity

There are certain substances that cannot be classified as solid liquid or gas e.g. porridge or a flower paste which are hereby coined 'the paste or porridge' Phase. There are also substances which cannot be classified as either solid, liquid or gas for example mealie meal, flour or face powder in the women beauty industry which are hereby classified as being in the 'Powder' phase.

DRIVERS OF PHASE CHANGE

- (1) Temperature variations e.g. normal atmospheric, extreme temperature e.g. in a solar absorber or steel making furnace or ice cold.
- (2) Pressure variations or repeated, 'pressure shocks' e.g. in a mealie meal grinding mill or stone crusher in the mining industry.
- (3) A combination of both temperature and pressure-hybrid causes

Solidifying or gasifying direction

Texture Change Spectrum

Smooth=1, Semi-smooth=2, Rough=3, with Holes=4

In chemical kinetics there exist mainly 4 study areas namely time, kinetic investigations, equilibrium and structural. The last 3 study areas are spatial and time is a variant that is linear within chemical kinetics (. Connors., 1990).

Reactants $\longrightarrow$ Final Product (Law of Conservation of Energy, First, Second and Third Laws of Thermodynamics being obeyed)

When 2 reactants or substances are involved in a chemical reaction, there could be alterations or variations in the following attributes :-heat content (enthalpy), color, taste, smell, phase changes, mass, outside texture, sound when hit with an iron object involving the materials whose rate of change (i.e. speed) must be measured and quantified numerically and therefore an eight dimensional description and analysis of kinetics could be a better, complete, exhaustive description that is informative of reaction kinetics. The reaction is said to be fully complete when all the 8 dimensions are no longer changing.

Complete color transformation / time taken which is chromatic kinetics.

Complete taste change/time=deliciomic kinetics

The word deliciomic being derived from the word, 'delicious'

The chromatic spectrum range

Colorless=0, White=1; Cream=2, Yellow=3; Orange=4; Red=5; pink=6; purple=7, green=8; grey=9; black=10

The deliciomic spectrum Range

Sweet=1; tasteless=2; sour=3 bitter=4; toxic=5

Smellionic Spectrum Range

SWEET SCENT=1, neutral smell like air=2, smelly=3, very uncomfortably odorous=4

Chromatic kinetics: rates of change of color as the reaction proceeds from initial reactants to final products

Tastionic kinetics: rates of change of tastes or toxicity from initial reactants upto final product

Smellionic kinetics: rate of change of smell of reactants in the process of a chemical reaction.

The word Smellionic being derived from the word, 'smell'.

Massionic kinetics for nuclear power stations which is change of mass in unit time.

Phaseonic kinetics: rate of change of phase

Thermionic kinetics is charge discharge rates of heat

Enthalpic kinetics: rate of change of phase

Equilibria kinetics- rate from one chemically stable state to another chemically stable state (with regard to reversible endothermic and reversible exothermic reactions)

Reaction momentum is mass of thermal energy storage material in reaction tank x kinetic velocity (chromatic, deliciomic etc).

Phaseonic Kinetics: Rate of change of phasde

Chromatic kinetical momentum = velocity of color change x mass of thermal energy storage material in tank or receiver

Tastionic kinetical momentum =velocity of change in taste x mass of thermal energy storage materials in reaction tank or boiler.

Smellionic kinetical momentum= smell change velocity x mass of thermal energy storage materials in the reaction tank

**CONTRIBUTIONS TO WORLD BODY OF KNOWLEDGE ON THE 8
DIMENSIONS OF REACTION DYNAMICS AND CHEMICAL KINETICS
(IN TERMS OF COINING THE NOMENCLATURE AND METHODS OF
CALCULATING THEM)**

$$\text{Chromatic kinetics} = \frac{(\text{final color} - \text{initial color})}{\text{time taken for the change}}$$

$$\text{Tastionic kinetics} = \frac{(\text{final taste} - \text{initial taste})}{\text{time taken for the change}}$$

$$\text{Smellionic kinetics} = \frac{\text{final smell} - \text{initial smell})}{\text{time taken for the change!}}$$

$$\text{Enthalpic kinetics} = \frac{\text{final enthlpy} - \text{initial enthalpy}}{\text{time taken for the change!}} = \frac{mc\theta_2 - mc\theta_1}{\text{time taken for the change!}}$$

$$\text{Massionic kinetics} = \frac{\text{final mass} - \text{initial mass}}{\text{time taken for the change!}}$$

$$\text{Texturionic-kinetics} = \frac{\text{final texture} - \text{initial texture}}{\text{time taken for the change!}} = \frac{\text{final roughness factor} - \text{intial roughness factors}}{\text{time taken for the change!}}$$

$$\text{Phaseonic kinetics} = \frac{\text{final phase} - \text{initial phase}}{\text{time taken for the change!}}$$

$$\text{Soundiotic kinetics} = \frac{\text{final noise level(dB)} - \text{initial noise level(dB)}}{\text{time taken for the change!}}$$

Total chemical kinetics = massionic kinetics x enthalpic kinetics x tastionic kinetics
x chromatic kinetics x Smellionic kinetics x texturionic kinetics x soundiotic kinetics
x Phaseonic kinetics

Two dimensional analysis of chemical kinetics

Chemical Kinetics = f(Spectrum Change, time, direction of change) = f(rate, direction)

SIZING OF ENERGY STORAGE TANKS

SENSIBLE HEAT

MATERIAL	SPECIFIC HEAT CAPACITY(J/kg/K)
Iron	0.451
Saturated Sand	1 632
Concrete	880
Stones	1 000
Thermal Oil	2 000
Sodium Nitrate	1 094
Potasium Nitrate	1 118

TABLE 22

MATERIAL	THERMAL CONDUCTIVITY(W/m-K)
Steel	45
Saturated Sand	2.56
Concrete	1.6
Stones	3

TABLE 23

On average, solar flux is available for 10 hours daily in Zimbabwe which implies that storage has to supply 500 MW for (24-10) =14 Hrs.

14x500MWh has to be stored during the daylight 10 hrs=7 000

7 000x60x60 J storage required=25 200 000 J

Given the specific heat capacity in J/kg/K and the density of storage of the material, the volume required can be calculated to store 25 200 000 J for Sensible heat material. For latent heat we need latent heat of liquification to compute the needed volumes. For thermochemical heat storage, we need heat of reaction per mole to compute the needed volume of the storage tanks.

STORAGE FACILITY SIZING

LATENT HEAT OF VAPORIZATION

Material	Latent Heat of Vaporization(Kj/kg)
Ammonia	1 369
Water	2 256
Methanol	1 100

TABLE 24

THERMOCHEMICAL HEAT STORAGE

The following materials are mixed to release thermal energy

- (1) Water and LiBr
- (2) Water and LiCl
- (3) Water and LiCl₂
- (4) Water and CaCl
- (5) Water and Zeolite 5A, water and Zeolite 13X, WATER and Zeolite 4A
- (6) Water and Silico Alumino Phosphate

Evaporate or heat water from the substance mixtures above using concentrated solar energy for thermal energy storage.

THE SIZING OF STORAGE TANKS

Assumptions

- (3) The thermal levels of the heat transfer fluid are raised from 600 °C to 1000 °C by the receiver which is also called the solar absorber
- (4) There is need for supplying the electricity grid with 500 MW for 14 hours
(2.25×10^{13} J of storage is needed).

From the thermal energy storage materials' specific heat capacities, one can compute the mass needed to produce 500 MW. From the material density and the above, one could compute and quantify the volume needed for the thermal energy storage tanks. If we assume a tank of height 10 m, one can compute or quantify the radius of the required tanks as follows: -

SALT	SPECIFIC HEAT CAPACITY	MASS	DENSITY	VOLUME	DIAMETER (10M HEIGHT)
Sodium Nitrate	1371 J/kg K	42 254 583 kg	2260 kg/m ³	18 790 m ³	50 m(MODULARIZE)
Potassium nitrate	1118.5 J/kg K	51 793 504 kg	2110 kg/ m ³	24 546 m ³	60m (Modularize)
Saturated sand	1 632 J/kg K	38 602 941 Kg	1 980 kg/m ³	19 497 m ³	50m

TABLE 25

Instead of one big tank, if one modularizes the tank to become 7 tanks, we will result in the following: -

SALT	DIAMETER
SODIUM NITRATE	1 tank 25m radius(too risky), or 7 tanks 10m radius or 30 tanks 5m radius
POTASIUM NITRATE	1 tank 30m radius, 9 tanks 10m radius or 40 tanks 5 m radius
SATURATED SAND	1 tank 25m radius(too risky), or 7 tanks 10 m radius or 30 tanks 5m radius

TABLE 26

Sodium Nitrate/Saturated Sand			Potassium Nitrate		
NUMBER OF TANKS	OF	RADIUS	NUMBER OF TANKS	OF	RADIUS
1		25	1		30
7		10	9		10
30		5	40		5

TABLE 27

LATENT HEAT

One can compute the needed mass to produce 500 MW from the latent heat of vaporization. One can compute and quantify the volume and hence size or dimension the thermal energy storage tanks from the material density.

MATERIAL	ENERGY PER KILOGRAM	KILOGRAMS REQUIRED	DENSITY	VOLUME	RADIUS assuming 10m high tank
MgCl ₂	1338 Kj/kg	2 072 000kg	2 320kg/m ³	894 m ³	5.35 m
KCl	5 960 000 Kj/kg	4 229kg	1 980 kg/m ³	2.1m ³	0.26m
NaCl					
NaCO ₃					
LiCO ₃					
KCO ₃					
KCL	31.31 kJ/kg	804 854 680 kg	1980 kg/m ³	406 493m ³	360m(not practical)

TABLE 28

MATERIAL	MELTING POINT	LATENT HEAT (Kj/kg)	SOLID SENSIBLE(Kj/kg)	LIQUID SENSIBLE(Kj/kg)	TOTAL HEAT (Kj/kg)
Magnesium Chloride	714 °C	454	0.1356	0.34023	454.48
Aluminum	660 °C	405	0.053	0.000055	405
Sodium Carbonate	851 °C	357	0.3396	0.2017	357
Lithium Carbonate	723 °C	45	0.1733	0.3902	45

TABLE 29

TANKS' VOLUME NEEDED FOR LATENT HEAT

PHASE CHANGE MATERIAL	Kg Required	Density	Volume	Diameter of Tank Assuming a 10 m high tank
Magnesium Chloride	55 506 608	2 320 kg/m ³	23 926 m ³	55m
Aluminum	62 359 276	2 700 kg/m ³	23 096 m ³	55m
Sodium Carbonate	70 743 716	2 540 kg/m ³	27 852 m ³	60 m
Lithium Carbonate	561 233 480	2 110kg/m ³	265 988 m ³	185m(not practical & lithium is very expensive)

TABLE 30

THERMOCHEMICAL HEAT STORAGE TANKS

One can compute and quantify the mass needed to produce 500 MW from the heat of reaction per mole. One can compute the volume of the required tank from the density of the material as follows: -

SALT	ENERGY PER KILOGRAM	KILOGRAMS REQUIRED	DENSITY	VOLUME	RADIUS(assuming 10m high)
CaCO ₃	14.52 kJ/kg	1 735 537 190.08	2 710 kg/m ³	640 419.63	142m(not practical)
LiBr plus H ₂ O	578.3 Kj/kg	43 575 999	3 460 kg/m ³	12 595m ³	21m
LiCl	-91.994 Kj/kg	2 739 310	2 160 kg/m ³	1 270m ³	6.4 m
CaCl ₂ plus water	656.8 Kj/kg-K	88 202	2 150 kg/m ³	17 845 m ³	24m

TABLE 31

A combination of for example latent heat storage and sensible heat storage exist at the same time for a given power plant as a hybrid storage in practice. Where 3 storage schemes i.e. thermochemical storage, latent heat storage and sensible heat storage co-exist on one power plant as a tri-coupled hybrid storage strategy, maximum benefits are obtained.

A deeper comprehension of reaction dynamics and chemical kinetics is needed for thermochemical thermal energy storage strategy. Chemical kinetics was divided into 8 parts namely massionic kinetics, Phaseonic kinetics, texturionic kinetics, soundiotic kinetics, Smellionic kinetics, tastionic kinetics, enthalpic kinetics and chromatic kinetics.

The change in color hereby coined ‘chromatic kinetics being seen as the speed or rate of change of color of reactants from colorless=0, white=1, cream=2, yellow=3, orange=4, pink=5, red=6, brown=7, purple= 8, green=9, grey=10, black=11 as the chromatic spectrum which in itself is a contribution to world body of knowledge. The rate of change of taste for edible products or reactants being termed tastionic kinetics with the following change spectrum: - tasteless=0, sweet=1, sour=2, bitter=3, repugnant=4 and poisonous=5.

Smellionic kinetics being the speed or rate of change of smell of the reactants with the following spectrum: - smell-less=0, sweet scent=1, odorous=2, stinking=3, poisonous=4.

Enthalpic kinetics being the observed speed or rate of change of heat content within the storage materials. These are the 4 among the 8 dimensions for analysis of chemical kinetics.

One could analyze 4 of the 8 Chemical kinetics as a 4 dimensional analysis as follows: -.

$$\text{Chromatic kinetics} = \frac{(\text{final color} - \text{initial color})}{\text{time taken}}$$

$$\text{Tastionic kinetics} = \frac{(\text{final taste} - \text{initial taste})}{\text{time taken}}$$

$$\text{Smellionic kinetics} = \frac{\text{final smell} - \text{intial smell})}{\text{time taken for the change!}}$$

$$\text{Enthalpic kinetics} = \frac{\text{final enthlpy} - \text{intial enthalpy}}{\text{time taken for the change}} = \frac{mc\theta_2 - mc\theta_1}{\text{Time Taken For the Change}}$$

Where m=mass, c=specific heat capacity, θ_2 =Final Temperature, θ_1 =Initial Temperature

$$\text{Phaseonic Kinetics} = \frac{\text{Final Phase} - \text{Initial Phase}}{\text{Time Taken For the Change}}$$

Where Solid Phase=1, Liquid Phase=2 and Gas Phase=3

Total chemical kinetics=Phaseonic kinetics x texturionic kinetics x soundiotic kinetics x enthalpic kinetics x chromatic kinetics x tastionic kinetics x Smellionic kinetics x massionic kinetics

Where any of the Kinetics above does not change, the change is ignored in the above equation so that the equation does not equal zero=0

Eight Dimensional analysis of chemical kinetics and reaction dynamics, their nomenclature and methods of calculating them is contribution by the author of this project to the, 'World Body of Knowledge.'

The operating thermal levels in the turbine is between 565 °C and 800 ° C . It was observed that liquids have higher specific heat capacities than solids within the ranges of temperature above, some materials like potassium nitrate and sodium nitrate will melt and evaporate implying that the liquification and evaporation latent heat are over and above the Sensible heat. This is the reason why they are the most extensively used heat storage materials.

CONCLUSIONS

Three basic thermal energy storage schemes have so far been considered for the proposed Solar Tower Power Plant which is alternatively known as the Central Receiver Tower Power Plant. These 3 technologies are (1) latent heat storage (2) Sensible heat storage and (3) Thermochemical heat storage schemes. The project recommended that a tricoupled thermal energy storage strategy be adopted and this involves or entails erecting all the 3 storage schemes for the proposed Kadoma Power Station in order to take care of long term, medium term and short term thermal energy storage needs of the power station. A tricoupled energy storage strategy exploits and gets all the advantages of all the 3 storage schemes for the benefit of one single Concentrated Solar Power Plant. The sensible heat storage scheme could undergo through maintenance whilst the latent heat and thermochemical heat storage supply the required thermal energy required for production of electricity during cloud cover and night conditions. Similarly, thermochemical and latent heat storage facilities can undergo through maintenance with no loss of generation during cloud cover and night conditions. This improves flexibility in maintenance programmes in addition to dispatch of power.

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The Chapter starts by discussing coal generation.

5.1 Developments in Coal Power Stations

INTRODUCTION

This section looks at developments in coal-fired power plants. The disadvantages and advantages of coal power plants are discussed. The section posits that coal is the cheapest fossil fuel and that it is readily available, a factor which has previously made it popular in many regions of the world. Coal power plants releases greenhouse gases which causes climate change and dangerous gases and byproducts which causes health problems in humans and other animals such as Sulphur dioxide and mercury. As a result of these complications, there is United Nations pressure through a series of annual COP meetings to phase out coal power generation. In Great Britain plans are there to phase out coal generation in the year 2024. The greatest producer of coal power in the world is China.

In Zimbabwe Harare Power station, Munyati and Bulawayo Power stations have been decommissioned, leaving Hwange as the only coal power plant.

The section concludes by recommending generation methods that may replace coal generation in Zimbabwe and also in countries like Mozambique with ocean coastlines.

MAIN NARRATIVE

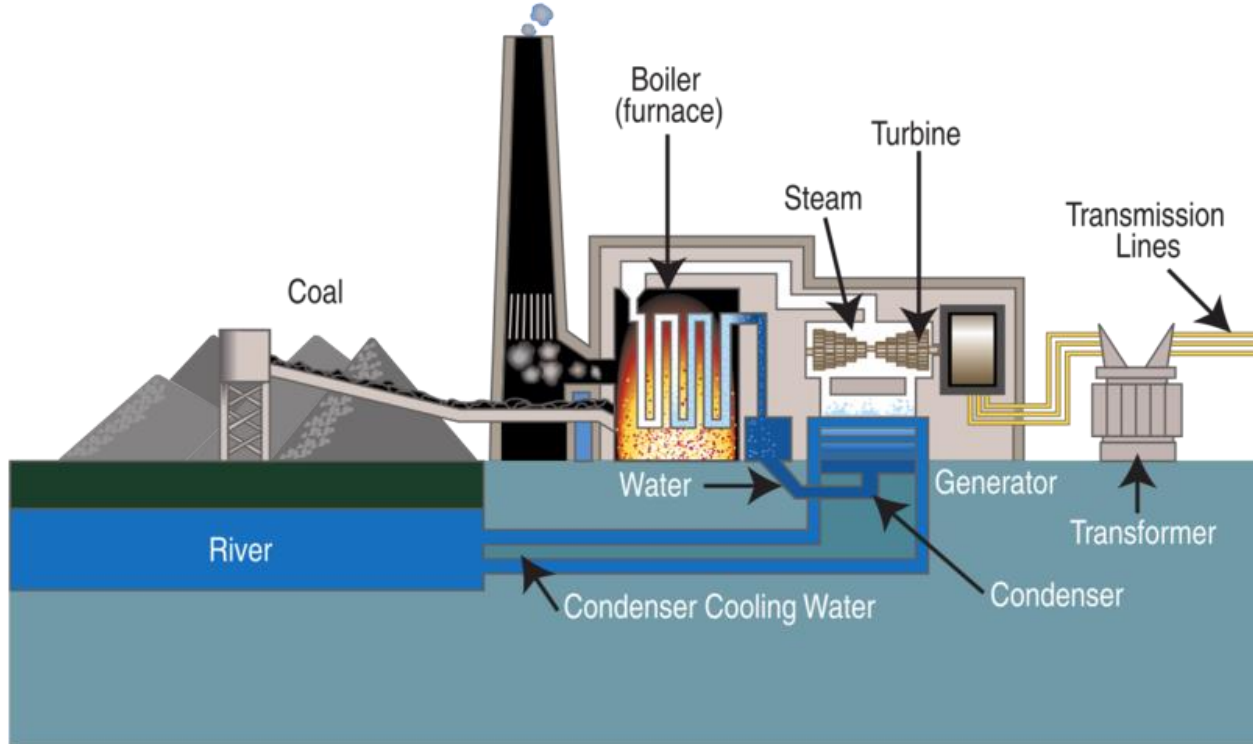


Figure 118

ESO (2024) posits that coal is a fossil fuel and the first coal power plant for public electricity was commissioned in 1882 by Thomas Edison in Great Britain.

Breeze (2014), says that coal fired power plants are comparatively expensive to construct since their construction includes both huge amounts of expensive materials like iron and steel and high volumes of labor. Breeze (2014), concludes that as a result the installation costs of a coal power plant will be vulnerable to fluctuating commodity and labor costs. Breeze (2014) again posits that coal is the cheapest among all fossil fuels and so the cost of its electricity is among the most competitive.

According to Obershelp et al. (2019), coal electricity production is the main driver of the emissions of toxic airborne and greenhouse gases into the atmosphere worldwide. Obershelp et al. (2019), further says that the closing down of the ten percent of coal power stations responsible for the most pollution by capacity reduces greenhouse emissions by sixteen percent or impacts on human health by sixty-four percent respectively.

Koornneef et al. (2008) highlights that one possible option for mitigating greenhouse gas emissions is the implementation of carbon dioxide capture and storage in coal

power stations and CO₂ is captured and sequestered in the underground for many years. Koornneef et al. (2008) posits that employment of coal fuel generation has other environmental effects like depletion of natural resources, eutrophication and acidification. According to Koornneef et al. (2008), the addition of CO₂ capture to coal power stations that are pulverized would reduce of the net electricity production efficiency and would increase emissions proportionally to air of substances that are not impacted by the capture process (ammonia and limestone for NO_x and SO_x reduction).

Koornneef et al. (2008) posits that the composition and quantity of emissions to soil, air and water would alter or vary when CO₂ capture is implemented on a coal fired power station. According to Koornneef et al. (2008), by-products, formation of wastes with other negative atmospheric effects and the consumption of resources, will up-scale, enhance or accelerate.

Thomas and Akhtar (2023) says that the world currently has 8500 coal power plants producing about 2000 GW of electricity with China's 3092 plants producing 1050 GW from coal which is larger than all other countries combined together in terms of output.

According to Energy Education report (2024), Coal power stations provide 40 % of the world's energy requirements and in South Africa it provides 94 % while in China and India 70 to 75 % of electricity is provided from coal power stations. Coal pollutes the atmosphere because of emissions leading to climate change. In 2018 in Zimbabwe 53.6 % of electricity was from hydro and 43.9 % was from coal. Plenty of coal is needed by coal power plants and about 1000 MWe requires 9000 tons of coal per day and so plants are located near coal mines. Coal power plants also need a lot of water to be circulated within the Rankine cycle and there is need to also locate coal power plants close to a body of water.

The steps in a coal power plant are as follows:

1. Unloading of coal
2. Pulverization of coal which is the process whereby coal is changed into powder by a mill. This guarantees almost full combustion of coal which maximizes thermal energy given off.
3. Inputting coal which is pulverized into the boiler and burning happens.
4. Transference of thermal energy to water which will be under pressure which then boils to steam

5. The steam is pushed through a turbine causing it to rotate very fast and this spins the generator thereby producing electricity

According to Energy Education report (2024), coal power plants use the Rankine cycle in order to complete the process.

Sims and Ferari (2019) says that about 80 % of the ash that come out of the combustion of coal is transported by the exhaust gases and precipitated to form fly ash. According to Sims and Ferari (2019), about 20 % of the other ash condenses within the furnace and settles at the bottom and agglomerates forming furnace bottom ash. The ash at the bottom of the Furnace is generally employed in the production of light-weight precast blocks of concrete. Breeze (2015) says that coal is cheap and readily available and this has previously made it popular in most regions of the world. According to Sulzer (2024), coal has the highest availability in occurrence and has a stable price and is the most cost-effective fossil fuel technology. According to Breeze (2015) two systems are employed for removing particulates from the flue gas of the coal power plant namely (1) electrostatic precipitators and (2) fabric filters.

According to Soeder et al. (2019), coal is closely pure carbon and when burnt releases carbon dioxide. Coal surface mining is greatly destructive to watersheds and landscapes.

The Energy Education report (2024) says that during the combustion of coal, a lot of pollutants are emitted for example oxides of nitrogen and Sulphur and particulate matter. It as well emits greenhouse gases like carbon dioxide and methane that causes climate change and global warming. There is need for technology which reduces these emissions like carbon capture and sequestration. According to Pandey (2020), the process of altering the carbon dioxide in the atmosphere into biomass carbon via the process of photosynthesis and the incorporation of this biomass into the earth's soil as organic matter is called carbon sequestration.

According to Tennessee Valley Authority report (2024), coal fired power plants give out electric power by burning coal inside a boiler in order to give out steam. The outputted steam will be under very high pressure and travels into a turbine that in turn rotates a generator which outputs electric energy. The water vapor or steam is subsequently cooled by a condenser and condenses back to water and sent back to begin the process again in the boiler. Tennessee Valley Authority report (2024) says that the steam is pumped to the turbines at pressures greater than 1800 pounds per square inch.



Figure 119

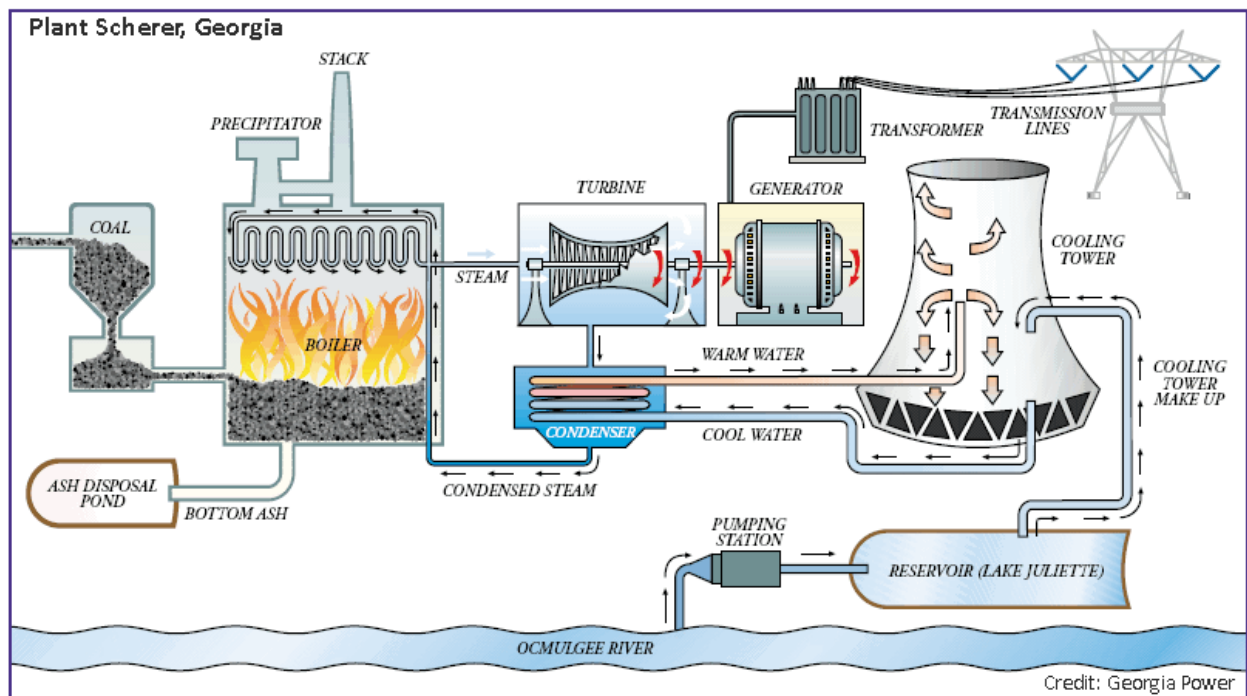


Figure 120

Global Energy Monitor report (2024) says that coal is grinded into fineness of talcum-powder and is burnt to upscale or increase the thermal levels of water and convert it into steam at high pressure and high temperature to rotate the turbo-generator set. Steam pressure introduces different versions such as supercritical, subcritical and ultra-supercritical versions of the combustion technology of coal which is pulverized. The Global Energy Monitor report (2024) says that the efficiencies of subcritical units are between 33 % and 37 % of energy in the coal is transformed into electric energy. The report further says that pressure at supercritical units is approximately 3530 pounds per square inch and the thermal energy levels are of about 565 °C. The Global Energy Monitor report (2024), supercritical coal plant efficiencies range spread from 37 % to about 40 %.

Pressures at ultra-supercritical units are about 4640 pounds per square inch with thermal levels at about 600 to 610 °C. Global Energy Monitor report (2024) says that recent research is targeting pressures of about 5300 to 5600 pounds per square inch with temperatures of about 700 to 720 °C with ultra-supercritical and this gives efficiencies of between 44 to 46 %. Fossil Energy and Carbon Management report (2024) says that an average coal power plant operates at 33 % efficiency.

According to U.S.A. Environmental Protection Agency report (2024), coal has small trace amounts of naturally occurring radioactive elements. The report says that when coal is burnt, the product waste contains small amounts of radioactive material which occurs naturally. The U.S.A. Environmental Protection Agency report (2024) says that the radioactive material is contained in 3 main waste streams called (1) boiler slag (2) bottom ash and (3) fly ash. These radioactive materials occur in so small quantities that no protection need to be taken.

Union of Concerned Scientists report (2019) posits that the formation of coal occurs deep underground over thousands of years whilst being exposed to high pressure and heat. The report says that coal is a black rock which is carbon-rich which emits thermal energy during combustion.

According to Union of Concerned Scientists report (2019) coal power plants causes air and water pollution as well as global warming. During combustion of coal, it emits pollutants and airborne toxins namely Sulphur dioxide, lead, mercury, carbon dioxide, particulates and nitrogen oxides. Union of Concerned Scientists (2019), posits that health effects of coal burning includes cancer, heart problems, neurological disorders, brain damage, premature deaths and asthma. Coal ash waste may ultimately be in lakes, ponds and landfills and may pollute drinking water sources and waterways.

Coal is mainly made up carbon and during combustion reacts with oxygen to form carbon dioxide –which traps heat that lead to global warming. Carbon dioxide behaves as a gas blanket in the atmosphere raising the earth's temperature to above normal limits. According to U.S. Energy Information Administration (2024), using coal damages the atmospheric environment. Sulphur dioxide which is released by coal power plants causes breathing diseases and acid rain. Nitrogen dioxide that is also a byproduct of coal power plants causes smog and respiratory diseases (U.S.A Energy Information Administration report (2024)). Particulates causes lung illnesses, breathing diseases, haze and smog. Other heavy metals and mercury are connected to developmental and neurological damage in other animals and humans. Fly ash and bottom ash may pollute groundwater.

The National Institute of Health report (2023) says particulate matter (PM_{2.5}) from coal consists of metals, black carbon and Sulphur dioxide which are deadlier or more dangerous when compared with emissions released from other alternative sources. According to the National Institute of Health report (2023), for every 1 g/m³ increase in coal (PM_{2.5}) mortality increased by 1.12 %. There was a reduction in coal deaths from 2013 to 2016 as a result of laws on pollution which diminished emissions in U.S.A. Keystone power plant in Pennsylvania was associated with 600 deaths per year which reduced to 80 per year after installation of emission scrubbers (National Institute of Health report (2023)).

The National Library of Medicine report (2021) says that the by-products of burning coal are cardiorespiratory toxins, endocrine disrupters and carcinogens.

According to ORR Protection report (2024), there is also a risky of fire in coal power plants. These complications are forcing the world to scale down or even phase out coal generation. There is need for de-carbonization of the electricity industry.

In 2019 only 1.6% of electricity in Britain was from coal generation and coal is marked for being phased out in Britain in the year 2024.

According to Perrin et al. (2015), oxy-combustion is competitive in terms of capture of carbon dioxide on power stations having coal as a fuel. The largest CO₂ capture costs are incurred in the Cryogenic Purification Unit and in the Air Separation Unit. Perrin et al. (2015) says that oxy-combustion has the highest efficiency, cost effectiveness and CO₂ recovery is above 95 %, CO₂ purity greater than 99.99 %. It has solid wastes, very limited liquid, zero chemical emissions, near zero air emissions and low water usage.

Perrin et al. (2015) says that significant improvements have been realized as a result of development of carbon dioxide capture on power stations that use coal as a fuel done over the last previous 10 years in collaboration with companies that manufacture boilers, thereby transforming them to be the most ideal in carbon capture as an option. Huge systems for flue gas purification and oxygen production are needed for oxy-burning in coal power stations. According Perrin et al. (2015), oxy-combustion has evolved in few years ago as a highly flexible and efficient option for CO₂ capture on boilers for steam and energy production. Starkloff et al (2015) says that no large scale oxy-fuel fired power station exist.

According to Viswanathan and Bakker (2001), the boiler or steam turbine's efficiency in coal power stations is strongly driven or influenced by steam pressure and temperature. There has been research to increase both since the 1970s. The encouragement to enhance efficiency has been caused by the need to reduce CO₂. Viswanathan and Bakker (2001) says that steam temperatures of the most efficient coal power stations are now in the 600 °C range which is about 60 °C increase in 30 years. Viswanathan and Bakker (2001) posits that the major enabling technology is the development of stronger high temperature materials with ability to operate under high stresses at ever increasing temperatures. High strength ferritic 9-12 Cr steels are now available commercially for temperatures of upto 620 °C. Ni-based alloys and austenitic steels are required for higher temperatures. Viswanathan and Bakker (2001) says that austenitic steels that are advanced for employment as reheater and super tubing are in existence on the market for thermal levels of upto 650 °C and possibly 700 °C.

Advantages of Coal Electricity Generation

1. Widely available in many places in the world including even in Zimbabwe.
2. Easiness of transportation from mines to power plants e.g. using rail or road or power stations can be located near coal mines
3. It's a very cheap energy resource
4. Its output can be very predictable and can be used to supply base load

Disadvantages of Coal Electricity Generation

1. Mines from which coal is dug can be dangerous (e.g. Hwange Mine Disaster) and unsightly.
2. Coal transportation by train or road pollutes the environment
3. Burning of coal causes greenhouse gases like carbon dioxide's release into the atmosphere that results in adverse change of climate or warming of the global village.

4. Burning of coal results in the release of polluting gases e.g. Sulphur dioxide which causes acid rain.
5. It is a non-renewable resource and can be depleted.
6. Coal dust causes lung diseases, pneumoconiosis and or emphysema in workers if they inhale a lot of coal dust.

Section Conclusion on Coal Generation

There is United Nations pressure through annual COP meetings to phase out coal generation because of the release of greenhouse gases that causes climate change which results from coal generation. Nuclear generation, solar thermal, wind and P.V. solar parks are possible replacements of coal generation in Zimbabwe whilst other countries near oceans like Mozambique may in addition also consider tidal and wave generation. Solar P.V. panel fields which are grid connected have started to make inroads in Zimbabwe e.g. the Centragrid power station at Nyabira. Flow-of-river technologies have not yet been exploited in Zimbabwe and these together with hydro-dam may also be expanded.

The project now proceeds with the discussion of results and the design summary.

CHAPTER 6

6.0 DISCUSSION OF RESULTS AND DESIGN SUMMARY

Introduction & Significance

This Chapter is the linchpin and summary of the design methodology. The design has a direct impact on the feasibility and success of building a Central Receiver Tower Power Plant in Kadoma District in Zimbabwe.

Design Consideration

- The chosen Heliostat layout is radial staggered and the receiver geometry is cylindrical.
- The Heat Transfer Fluid is molten salt i.e. a mixture of potassium nitrate and sodium nitrate in the ratio 3:2 because of high specific heat capacity which reduces the size of the thermal energy storage tanks.
- The thermodynamic power cycle is the Rankine cycle.
- Materials for the tower is reinforced concrete and heliostat support-steel members in order to reduce wind forces
- Materials considered for the receiver include rough aluminum painted with graphite mixed with black paint, uranium-nickel cermet, aluminum graphite, metallic plasmonics, carbon-like diamond thin films and aluminum substrates and the chosen material is uranium-nickel cermet. Aluminum and associated compounds were not chosen because of low melting points

MATERIAL	MELTING POINT
1. Aluminum	660.3 °C
2. Uranium	1 132 °C
3. Nickel	1 455 °C
4. Diamond	4 500 °C

TABLE 32

- Structural integrity of the central tower, control room and thermal energy storage tanks is critical
- Tower stability is guaranteed by considering wind forces, weight of construction materials and possible historic seismic activities of the area e.g. earthquake.
- Safety and Maintenance-Safety clearances from thermal energy storage tanks and pipes or tubes containing hot fluids will be 50m during operation at 565 °C. In the step-up substation no person is allowed to work on any high voltage equipment unless that equipment is fully isolated from all sources of electricity supply, tested for dead, earthed from all sides surrounding the work place from which direction electricity can come from and released for work under a permit to work. All low voltage, low temperature and low pressure equipment in the control room will be worked on under a limitation of access document. No work on hot metallic work e.g. thermal energy storage tank or pipes containing hot fluids can be worked on unless all the valves and electric motors supplying hot fluids are closed and turned off respectively, temperatures tested to be below 30 °C and trucks with cold water sprays are nearby.
- Maintenance considerations. Ladders inside steelwork of the tower from ground to solar absorber will be installed. Cranes fitted with ropes and chains for lifting the solar absorber tank shall be fitted on top of the tower.
- Access points shall be provided to all equipment and equipment's' components that may need future maintenance.

Thermal Energy Storage tank

- Molten salt used is a mixture of potassium nitrate and sodium nitrate in the ratio 3:2 respectively. The specific heat capacity of potassium nitrate is 1.118 J/g °C. The specific heat capacity of sodium nitrate is 93.05 J/mol K which are high enough to ensure smaller thermal energy storage tanks. It ensures relatively efficient dispatchability of thermal energy since potassium and sodium are better thermal conductors than water and is pumped by electric pumps along tubes from receiver to heat exchanger.

CENTRAL RECEIVER TOWER POWER PLANT DESIGN

Introduction

Full Picture of the Heliostat Mirror Field & Central Tower



Figure 132



Figure 133

The Single Tower Central Receiver Tower Power Plant- This Plant is less Efficient than a multitower Power Plant

Drawing of the Central Receiver Tower Power Plant with partial view of the Heliostat mirror field

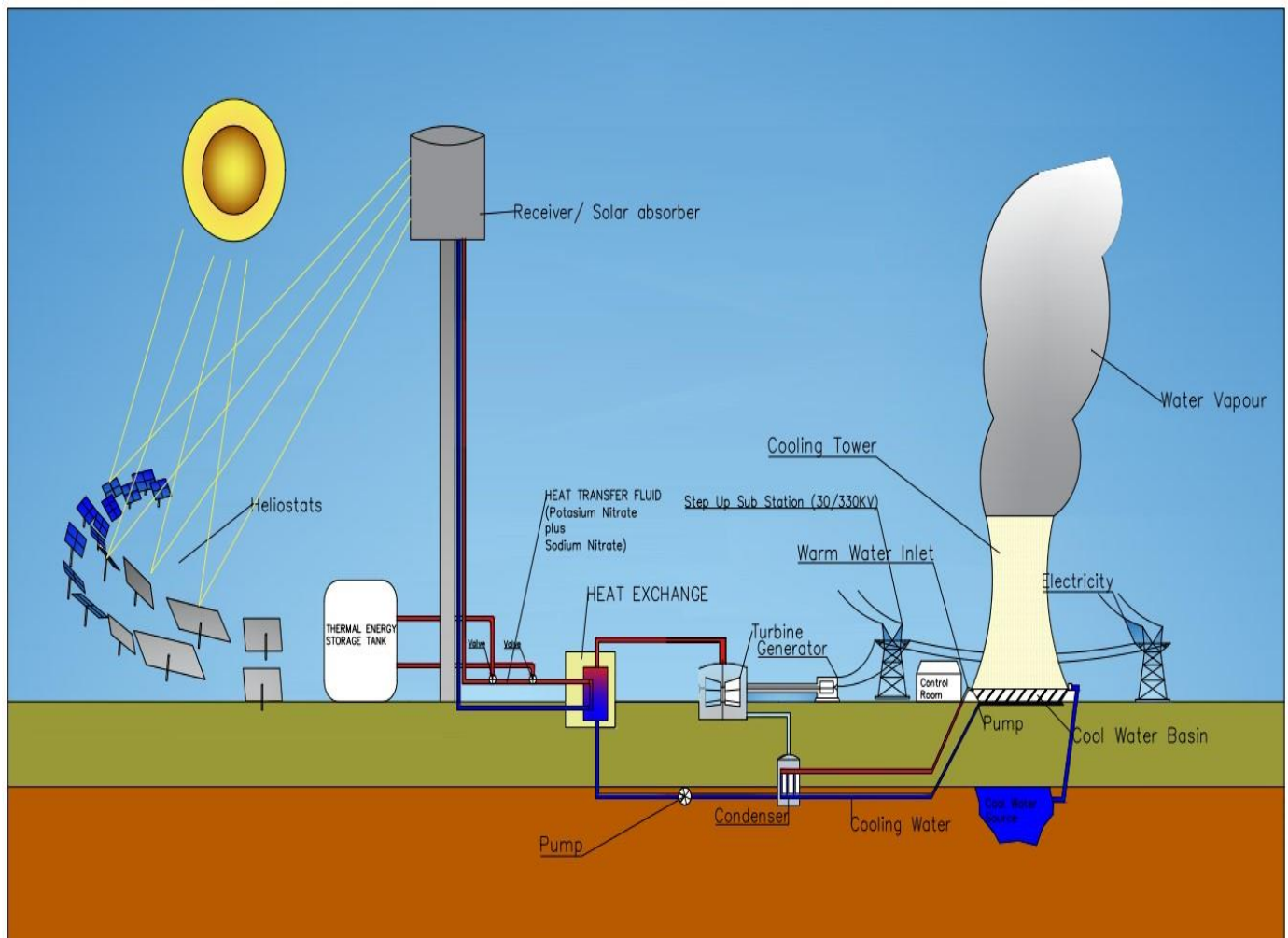


Figure 134

Explanation of the Pictorial Diagram

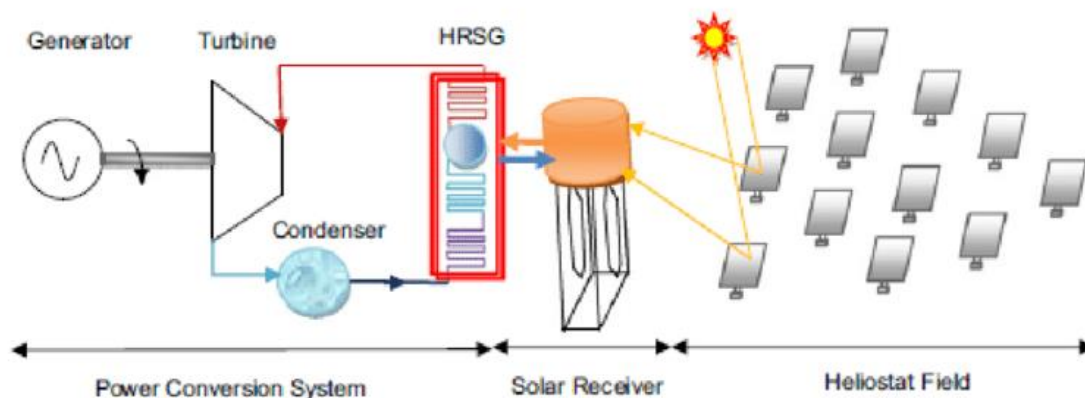
The heliostats above, which are partly shown, reflect and focus the sun's rays onto the stationary solar absorber on top of the Central tower throughout the day as the sun moves from morning to evening except during the night time and also cloud conditions. The molten salt contained in the solar absorber which is also called a receiver is heated to about 565 °C or even 600 °C to allow for heat losses in the transmission pipes from the absorber to the heat exchanger. The molten salt is then pumped down the tower to the heat exchanger or thermal energy storage tanks by electric pumps through valves which can be opened or closed manually or electronically in response from the pressure from the storage tank, maintenance demands or time of day.

The heat exchanger transfers heat from the Heat transfer fluid which is molten salt to the working fluid which is water which is steamatized and expands about 1700 times in volume creating great pressure through nozzles directed on turbine blades. The momentum of moving steam rotates the turbine-generator set generating electricity in the process. Steam from the turbine is cooled by the condenser and recirculated again.

The generator feeds the step-up substation which dispatches electricity into the grid. The cooling tower cools water in the condenser.

Figure

138



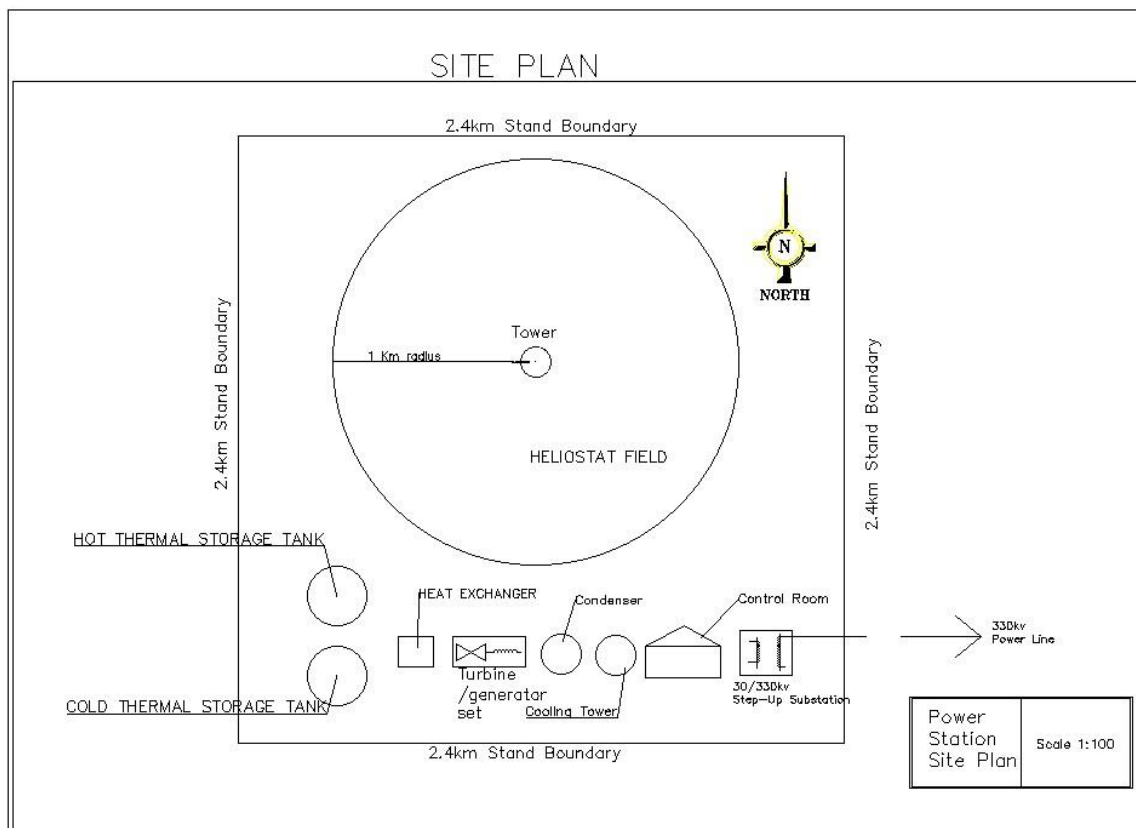


Figure 139

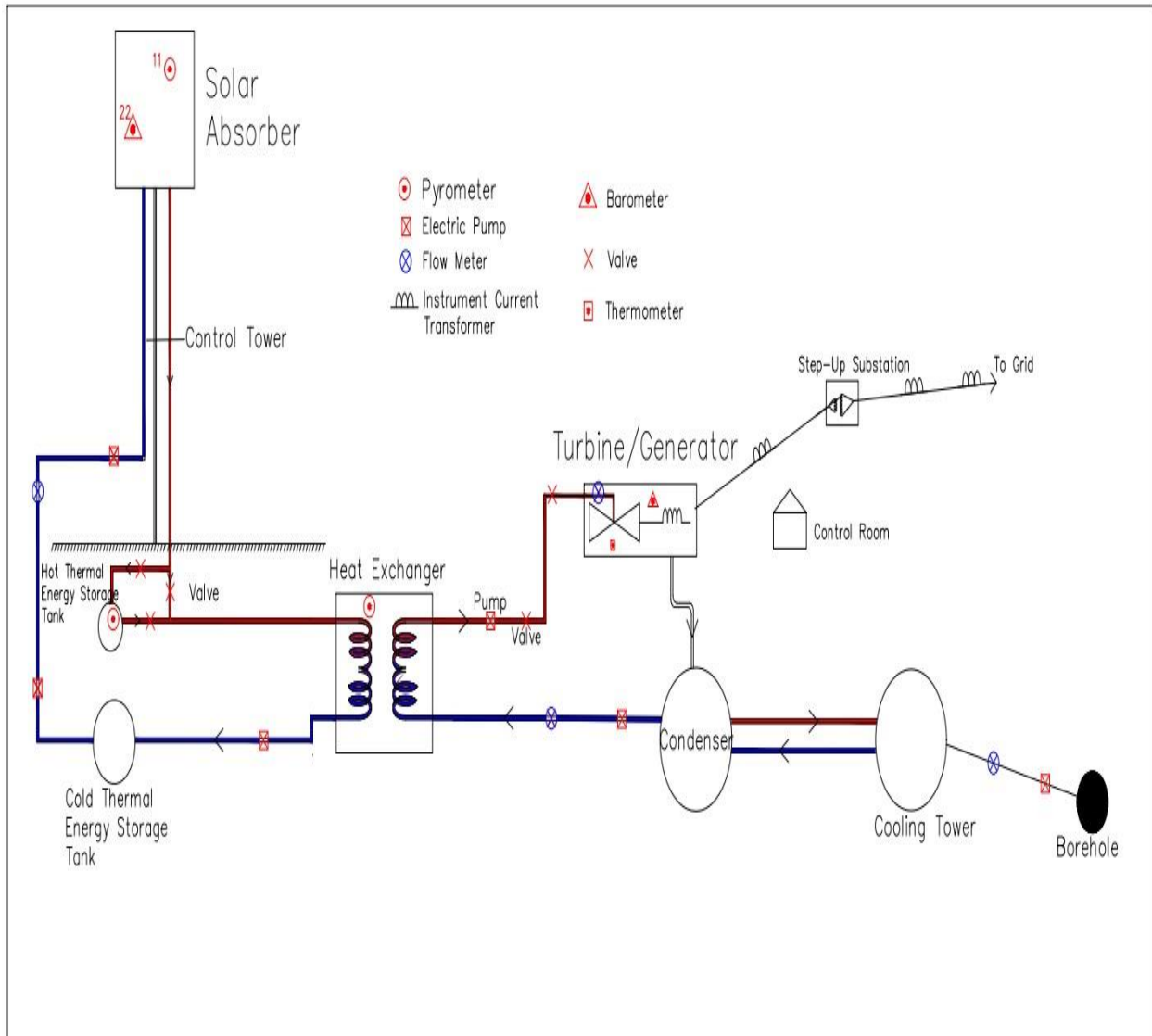


Figure 140

COMPONENTS OF A CENTRAL RECEIVER TOWER POWER PLANT

- **Heliostat mirror field**-for trapping and focusing the sun's rays onto the solar absorber
- **Central Tower**-for supporting the solar absorber onto a suitable position
- **Thermal Energy Storage tank**-storing hot molten salt (potassium nitrate & sodium nitrate)

- **Heat Exchanger**-for transferring heat from the thermal energy storage fluid which is molten salt (mixture of potassium nitrate & sodium nitrate) to the working fluid which is water
- **Turbine/generator set**-for converting heat to rotational mechanical energy to electrical energy
- **Condenser**- for converting steam to water so that the cycle starts all over
- **Cooling Tower**-for cooling water from and to condenser
- **Control Room**-for the power station & substation controls
- **Step-Up substation**-for stepping up the voltage to reduce heat losses (I^2R losses) during transmission

The sun in Zimbabwe rises from East to West almost vertical in summer and slightly North in winter. Therefore, the thermal energy storage tanks, the control room, the turbine/generator room, the step up substation and cooling tower are on the South of the heliostat field so that they don't cast shadow on heliostat mirrors throughout the year.

Bill of Materials

1. Central Receiver Tower
2. Solar absorber
3. Cooling Tower
4. Thermal Energy Storage tanks
5. Steel for heliostat supports
6. Stepper motors
7. Heliostat mirrors
8. Control room
9. Turbine generator room
10. inclinometers
11. 2 of 30/330 kv 250 MVA transformers
12. 2 of 30 kv breakers
13. 2 of 330 kv breakers
14. 2 of 30 kv isolators
15. 2 of 330 or 400 kv isolators
16. 2 transformer pads
17. 4 breaker pads
18. 4 isolator pads
19. M of copper conductors and busbars
20. M of copper for earth grid

21. M for 4 earth mats.
22. M of catenary wires
23. Busbar conductors
24. Substation fence
25. Power station boundary fence
26. M of substation boundary fence
27. Kg of substation stone
28. 4 flowmeters
29. 4 pyrometers
30. 2 tachometers
31. 3 barometers
32. 4 electric pumps
33. 6 valves
34. Steel tubes for water to cooling tower
35. 240 m high steel tower (4 x 4 x 240 m)
36. 2 580m long steel tubes with diameter 1 m
37. 6 000 000 m² of reflecting glass
38. 42 858 heliostat stands 4m high (20cm diameter) steel rods
39. 42 858 heliostats electric motors for moving heliostats
40. 2 storey, 8 rooms control room
41. 2 steel thermal energy storage tanks 60m diameter and 10 m tall
42. One heat exchanger
43. 500 MW turbine
44. 500 MW generator
45. condenser
46. condenser room
47. potassium nitrate (14 143 m³)
48. Sodium nitrate (14 143 m³)
49. Litres of water
50. Overcurrent relays
51. Differential relays
52. Arcing horns
53. Surge arrestors
54. 4 instrument current transformers
55. 4 instrument voltage transformers
56. 110 V D.C. Batteries
57. Substation fence
58. M conduits
59. 1.5 mm copper cables
60. 2.5 mm copper cables

- 61. Electricity plugs
- 62. ECO steel rods
- 63. NEXUS steel rods
- 64. Sewer pipes
- 65. Water pipes
- 66. CISCO switch
- 67. Patch panels
- 68. Brush tides
- 69. UTP networking cables
- 70. Cabinets
- 71. WIFI broadcaster
- 72. WIFI Receiver
- 73.2 Pyrometers which can measure up to 1000 °C
- 74.6 Electric Pumps
- 75.4 Flowmeters
- 76.2 Barometers
- 77.1 Thermometer
- 78.4 Instrument Current Transformers
- 79.4 Instrument Voltage Transformers
- 80.600m molten salt pipes or tubes
- 81.350 m hot and cold water pipes

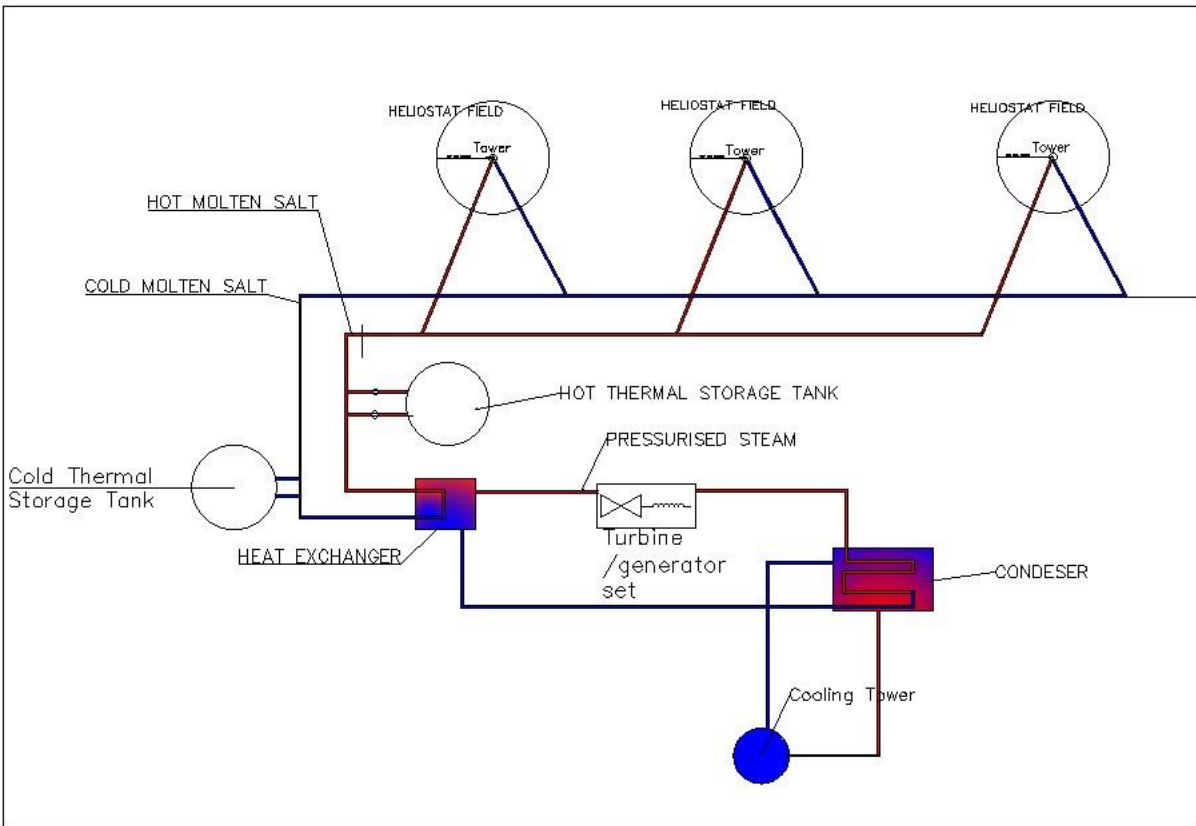


Figure 141

HELIOSTATS

Heliostats are mirrors that are strategically moved or rotated East-West or North-South by d.c motors controlled by a computer programme in Arduino to ensure autofocus of the sun's rays onto a stationary solar absorber throughout the whole day as the sun moves East-West daily and North-South seasonally. Their design, tracking and autofocus efficiency are crucial for optimal operation of the Central Receiver Tower Power Plant. Different heliostat types exist and optimization of their performance ensures maximum collection of solar energy.

The first generation of mirrors were 40 m²

The second generation was 44-57 m²

And the third generation of heliostat mirrors is 100 m²

The mirrors have a lifespan of 30 years.

HELIOSTAT tracking

Solar trackers are placed at 8 strategic positions i.e North, South, East, West, North-East, North-West, South East, South West of the heliostat field where it can directly face the sun without any shadow. This gives the sun vector. The solar trackers communicate among themselves for majority or consensus position and then the transceiver broadcasts the solar vector to all heliostat mirror controllers Use is then made of the solar vector and absorber vector from each heliostat mirror. Mirror normal = $\frac{1}{2}$ (sun vector + receiver vector) from each heliostat which gives the normal to each heliostat. The solar absorber or receiver vector is fixed, stationary and therefore constant. The normal of the mirror is calculated as half of the sum of the sun vector and the solar absorber vector measured from each heliostat mirror from the horizontal East. Two d.c. motors move the heliostat mirror East-West and North-South via vertical. The sun is very far away from the power station and the sun vector from each heliostat is considered the same.

Each heliostat mirror support structure has two d.c. motors, transceiver, inclinometer, Arduino controller containing a 'C' Language program for controlling the two stepper motors' rotation or movement.

TWO AXIS SOLAR TRACKER

- The amount of energy or solar flux collected by heliostat mirrors can be enhanced by 40 % due to dual axis tracking
- Solar tracking enables the sun's rays to fall on the solar panel at 90 ° throughout daytime.

- Tracking should enable heliostat to move EAST-West daily and North-South seasonally.

SET-UP OF SOLAR TRACKING

- Light Dependent Resistors (LDR) possesses infinite resistance in dark conditions.
- The LDRs resistance goes down to about 300 ohms when sunlight falls on the LDR directly.
- Tracking needs two d.c. motors
- Four LDRs on Quadrant sensor are needed-light Dependent Resistor is a semiconductor resistor
- The sun will be automatically tracked using a control program
- The East-West light dependent resistors possesses equal resistance when the sun is 90° to the panel.
- East and West voltages feed to analog inputs.
- When the sun position shifts to the West then $V_{\text{west}} < V_{\text{east}}$
- If the difference: $V_{\text{west}} - V_{\text{east}} > V_{\text{sensitive}}$, move or rotate Westwards.
- Move Westwards until difference $V_{\text{east}} - V_{\text{west}} < 0$
- Two relays are required by each D.C. motor to shift or rotate in earlier direction and normally employ a gearbox.
- The tracking program employs continuous surveillance of East-West then North-South voltages and takes appropriate corrective action.

MECHANICAL MECHANISM FOR DUAL AXIS SOLAR TRACKING



Figure 142

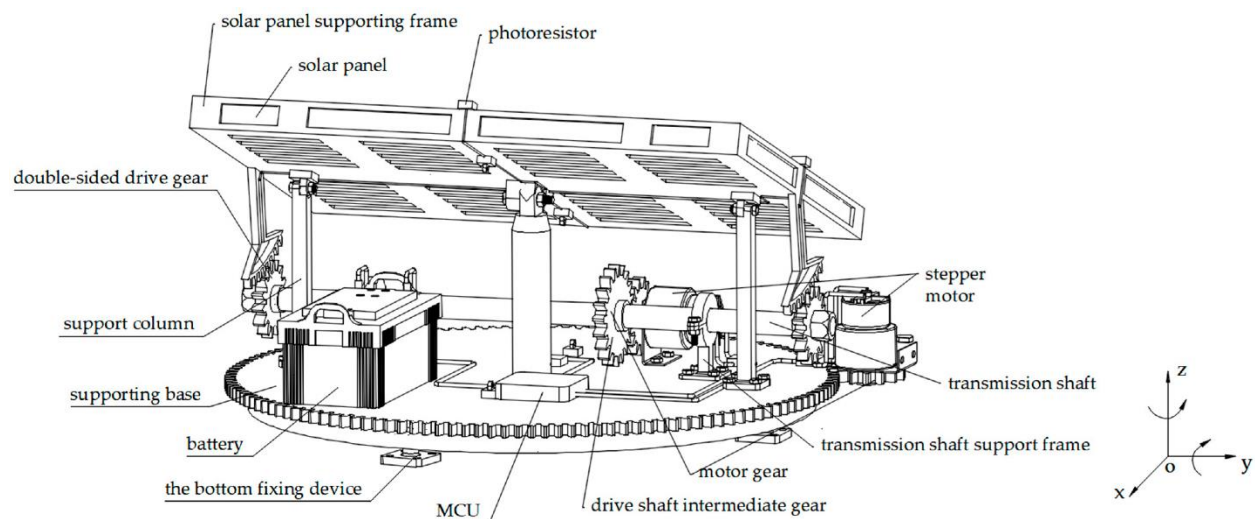


Figure 143

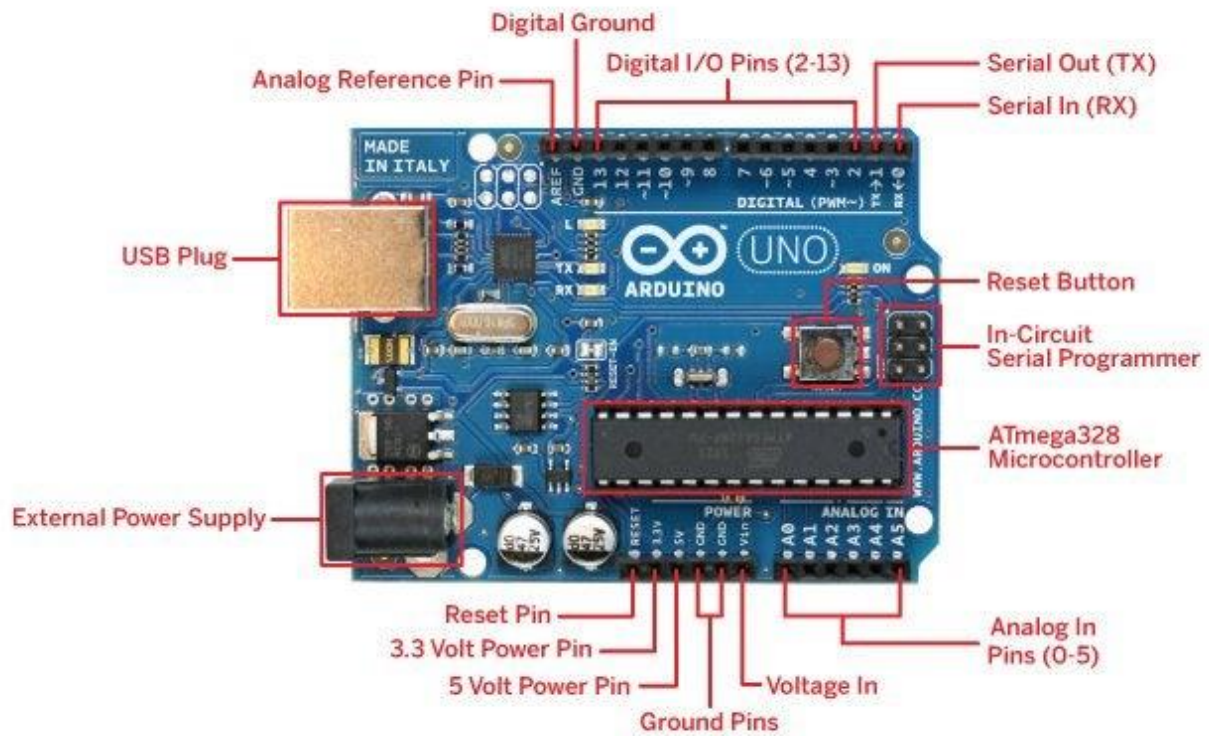


Figure 144

Solar TRACKING PROGRAMME

```
void east_west() {  
  word east_ldr,west_ldr,sensitivity;  
  east_ldr = analogRead(EAST_LDR);  
  west_ldr = analogRead(WEST_LDR);  
  sensitivity=analogRead(SENSITIVITY);  
  if (abs(east_ldr - west_ldr) > sensitivity) {  
    if (east_ldr > west_ldr) {  
      digitalWrite(MOVE_WEST,HIGH);  
      do  
        east_ldr = analogRead(EAST_LDR);  
        west_ldr = analogRead(WEST_LDR);  
        sensitivity=analogRead(SENSITIVITY);  
      while (east_ldr - west_ldr > 0);  
      digitalWrite(MOVE_WEST,LOW);  
    } else {
```

```
    } else {  
        digitalWrite(MOVE_EAST,HIGH);  
        do  
            east_ldr = analogRead(EAST_LDR);  
            west_ldr = analogRead(WEST_LDR);  
            sensitivity=analogRead(SENSITIVITY);  
            while (west_ldr - east_ldr > 0);  
            digitalWrite(MOVE_EAST,LOW);  
        }  
    }  
}
```

The void function north_south() is similar

```
void loop() { // this continuously tracks the sun  
    east-west();  
    north_south();  
}
```

STEPPER MOTOR PROGRAM

```
#define C1P 7
#define C1N 6
#define C2P 5
#define C2N 4
int torque = 3;
int gap = 20;
enum states {idle, state_0,state_1,state_2,state_3};
enum states stepper_state = idle;

void clockWise (int notch_count) {
    int count_notches;
    for (count_notches = 0; count_notches < notch_count;
        count_notches++) {
        switch (stepper_state) {
            case idle : digitalWrite(C1P,HIGH);
                        stepper_state = state_0;
                        delay(torque);
                        digitalWrite(C1P,LOW);
                        break;
            case state_0 : digitalWrite(C2P,HIGH);
                        stepper_state = state_1;
                        delay(torque);
                        digitalWrite(C2P,LOW);
                        break;
            case state_1 : digitalWrite(C1N,HIGH);
                        stepper_state = state_2;
                        delay(torque);
                        digitalWrite(C1N,LOW);
                        break;
            case state_2 : digitalWrite(C2N,HIGH);
                        stepper_state = state_3;
                        delay(torque);
                        digitalWrite(C2N,LOW);
                        break;
            case state_3 : digitalWrite(C1P,HIGH);
                        stepper_state = state_0;
                        delay(torque);
                        digitalWrite(C1P,LOW);
```

```

        break;
    }
    delayMicroseconds(gap);
}
}

void setup() {
    Serial.begin(9600);
    pinMode(C1P, OUTPUT);
    pinMode(C1N, OUTPUT);
    pinMode(C2P, OUTPUT);
    pinMode(C2N, OUTPUT);
    digitalWrite(C1P, LOW);
    digitalWrite(C1N, LOW);
    digitalWrite(C2P, LOW);
    digitalWrite(C2N, LOW);
    delay(1000);
}
// anticlockwise is towards the motor
void anticlockWise (int notch_count) {
    int count_notches;
    for (count_notches = 0; count_notches < notch_count;
        count_notches++) {
        switch (stepper_state) {
            case idle : digitalWrite(C1P,HIGH);
                        stepper_state = state_0;
                        delay(torque);
                        digitalWrite(C1P,LOW);
                        break;
            case state_0 : digitalWrite(C2P,HIGH);
                        stepper_state = state_3;
                        delay(torque);
                        digitalWrite(C2P,LOW);
                        break;
            case state_1 : digitalWrite(C1N,HIGH);
                        stepper_state = state_0;
                        delay(torque);
                        digitalWrite(C1N,LOW);
                        break;
            case state_2 : digitalWrite(C2N,HIGH);

```

```

        stepper_state = state_1;
        delay(torque);
        digitalWrite(C2N,LOW);
        break;
    case state_3 : digitalWrite(C1P,HIGH);
        stepper_state = state_2;
        delay(torque);
        digitalWrite(C1P,LOW);
        break;
    }
    delayMicroseconds(gap);
}
}

// the loop routine runs over and over again forever:
void loop() {
    Serial.println("Going Clock wise away from motor");
    clockWise(6000);
    delay(1000);

    Serial.println("Going Anti Clock wise towards motor");
    anticlockWise(6000);
    delay(1000);
}

```

COST/BENEFIT ANALYSIS

ITEM/COMPONENT	ESTIMATED COST(U.S. \$)
Tower	800 000
Receiver	20 000
Heliostat Mirror Assembly	142 000 000
Storage Tanks	20 000
Heat Exchanger	10 000
Condenser	10 000
500 MW Turbine	20 000
500 MW Generator	20 000
Step-up Substation	100 000
Cooling Tower	20 000
Substation Fence	10 000
Power Station Boundary Fence	20 000
Molten Salt	5 000
Electric pumps	10 000
Tubing and Piping	10 000
Water	200
Labor	2 200 000
Transport	30 000
Control Building	70 000
Measurement and Control Equipment	20 000
Land	150 000 000
Maintenance Costs	10 000
Subtotal	295 405 200
5 % Admin Costs	14 770 760
Total Costs For the Project	310 175 960

Approximately U.S. \$310 million

Costs have not been done in ZIG which is the local Zimbabwean currency because year on year inflation levels are high 191%. An inflation level of 2 % on the US \$ has been assumed. 310 175 960 in 5 years (3 years construction period + 2payback period) will be U.S. \$342 459 323.

TABLE 33

Zimbabwe Electricity Supply Authority's tariff =\$0.11/KWh

A 500 MW power station produces 500 000 kWh per hour

There are 12 hours a day and 7 days in a week and 52 weeks per year=4 368 hours per year

In 1 year the 500 MW will supply $500\,000 \times 4368 = 2\,184\,000\,000$ kWh

This gives $2\,184\,000 \times 0.11$

Giving U.S. \$240 000 000

Payback period $\frac{343}{240} = 1.43$ years which is lucrative which is approximately =2 years

Life Expectancy of the plant=40 years

Cost of Project=y

Revenue per year =x

Payback period= $\frac{y}{x}$

The design impact on cost, efficiency and electrical power output. The overall project cost is high and so does the returns in terms of monetary value and climate change avoidance benefits.

Levelized Cost of Electricity

The levelized Cost of electricity is calculated by dividing the present value of all costs over a power plant's lifetime by the present value of all electricity generated over the same period. The power plant's life time =40 years of generating 500 MW = $500 \times 24 \times 365 \times 40 = 175\,200\,000$ MWh generated in 40 years= $175\,200\,000\,000$ kWh

If we assume present value operational costs=100 000 000million per year
maintenance costs = \$100 000 000 per year
Admin costs=\$45 677 034 m per year
and construction costs=343 m

All Costs= $(100\,000\,000\text{m} + 100\,000\,000\text{m} + 45\,677\,034) \times 40 + 343 = \$10\,512\,000\,000\text{m}$

Therefore, levelized Cost of electricity= $10\,512 / 175\,200 = \text{U.S. } \$0.065 \text{ per kWh}$

Estimated Efficiencies

Reflectivity of mirrors=0.91
Absorptivity of receiver= 0,80
Shading elimination efficiency=0.75
Blocking elimination efficiency=0.8
Heat losses in pipes and tubes efficiency= 0.65
Heat Engine Efficiency=0.705
Therefore, Plant Efficiency=0.2= 20 %

RECEIVER TECHNOLOGY

The solar absorber or Central Receiver converts sunlight into high-temperature thermal energy. The selection and choice of receiver material, its geometry and heat transfer mechanisms impacts on overall efficiency. Selection of the right material for a solar central receiver is crucial for its performance and longevity.

KEY CONSIDERATIONS ARE: -

(a) High temperature strength.

Solar receivers operate under extreme heat conditions thereby enduring high thermal stresses. The following materials are recommended as they would offer excellent high temperature strength, making them suitable candidates: -

- (1) Rough aluminum painted with black paint mixed with graphite powder
- (2) Cermet e.g. Urania-nickel cermets
- (3) Thin films of aluminum substrates
- (4) Diamond-like carbon
- (5) Rough selective inhomogeneous and low cost aluminum graphite
- (6) Metallic plasmonics.

For this design rough aluminum painted with graphite powder mixed with black paint is chosen because of the light weight of aluminum.

(b) Corrosive Resistance

The receiver tubes are exposed to heat transfer fluid in our case molten salt (i.e. mixture of potassium nitrate and sodium nitrate). Urania-nickel cermets become attractive in this regard.

© Thermal conductivity

Excellent heat transfers from the receiver to the molten salt to working fluid which is water in our case is essential, imperative and necessary. The following materials have high thermal conductivity for enhanced overall system performance

- (1) Graphite
- (2) Diamond
- (3) Aluminum

KEY CONSIDERATIONS FOR THE THERMAL ENERGY STORAGE FLUID

(a) Specific Heat Capacity

A high heat capacity of the thermal energy storage fluid (molten salt) allows efficient energy storage. A mixture of potassium nitrate and sodium nitrate exhibit favorable heat capacities thereby enabling effective energy transfer from the receiver to the heat exchanger to the water working fluid. The specific heat capacity of potassium nitrate is $1.118 \text{ J/g } ^\circ\text{C}$ and sodium nitrate is 93.05 J/(mol K)

(b) Freezing Point

The Heat Transfer Fluid (HTF) should remain liquid even as low temperatures drop to ensure a year-round operation capability.

(c) Viscosity

Low viscosity facilitates fluid flow through pipes and components.

(c) Corrosion Resistance

The Heat Transfer Fluid (HTF) should not corrode receiver tubes or other system components. Proper selection of materials and prudent system design prevent corrosion.

(d) Thermal Conductivity

Efficient heat transfer from the receiver to the HTF is essential and molten salt has reasonable thermal conductivity.

€ Cost and Availability

The heat Transfer Fluid plays a crucial role in energy storage and transfer within the solar Central Tower system and a tradeoff between desirable properties and cost has to be struck.

THERMAL ENERGY STORAGE

Efficient and effective storage of high-temperature energy is essential, vital and important to ensure a smaller geographical space and reduction of the cost of storage tank material. Molten salt tanks or other storage methods allow Dispatchability of electricity generated when the sun is not shining. It is therefore important that when designing thermal energy storage (TES) for Central Tower solar power plants several critical considerations come into play.

There is need to choose an efficient and cost effective storage medium. It must be capable of withstanding strong heat and high temperatures.

HEAT TRANSFER EFFICIENCY

There is need to optimize heat transfer between receiver and storage medium e.g. making the inside of the receiver rough and painted black. Roughness increases surface area in contact between receiver material and HTF. Proper design ensures minimal heat losses during charging and discharging cycles. There is need to insulated the storage tanks and tubes for HTF and working fluid.

THERMAL INSULATION

There is need to insulate storage tanks and pipes where HTF and working fluids flow in order to minimize heat losses. Materials considered for insulation include the following

1. Asbestos
2. Fibre glass
3. Mineral wool
4. Thermaxx jackets
5. Aerogel e.g. pyrogel XT.

The installation of insulation material on the outside of storage tanks and tubes or pipes in which HTF and working fluid flows prevents unnecessary heat energy dissipation.

STORAGE CAPACITY

The storage capacity depends on plant operational requirements, grid demand (i.e. 500 MW in our case), and solar availability (about 10 hours a day on average). Larger capacity allows for longer operation time during cloudy conditions and night periods.

CHARGING AND DISCHARGING

To balance (energy input-charging) and (energy output-discharging) we need to consider the balance. Efficient control systems manage these processes to match electricity demand.

THERMAL STRATIFICATION

It is important that the system promotes uniform temperature distribution in storage medium. Use of deformed steel bars, rods or fins within the storage tanks may assist in ensuring uniform heat distribution within the molten salt in the solar absorber and storage tanks. Proper thermal stratification prevents destructive thermal gradients or localized hot spots and enhances overall efficiency.

LIFETIME AND DURATION

There is need to select materials that withstand thermal cycling and chemical reactions. Durability ensures long term thermal energy storage performance.

HEAT EXCHANGER

It is a bundle of hollow pipes or tubes which is contained inside a cavity in order to increase the surface area where heat is transferred from molten salt to water.

SAFETY MEASURES

The following safety measures should be taken to prevent leaks, accidents related to storage medium that we are going to implement.

1. No person shall work on any hot equipment unless, all valves from hot fluids to the point of work are closed, the equipment is cooled and its temperature is under 30 °C.
2. Mechanically strong materials such as steel shall be used to construct the thermal energy storage tanks.
3. Construction of the tall Central Tower need to be done in non-rainy season to prevent lightning strike of workers

THERMODYNAMIC POWER CYCLE

The power tower system converts stored thermal energy into electricity using thermodynamic cycle (e.g. Rankine steam cycle or Supercritical CO₂ cycle. If water is employed as a working fluid, which is indeed this project's recommendation, then the steam cycle is called Rankine cycle.

SUN POSITION AND RADIATION

Precise calculations of solar radiation and sun position are critical during design. These factors influence heliostat placement, receiver orientation and overall system performance. Such calculations are important in the design.

Structural Integrity and Materials

The tower structure, heliostat supports and receiver materials must withstand high temperatures, wind loads and thermal stresses. Durability and maintenance easiness plays a significant role.

When considering structural integrity and materials for a central tower solar plant, some of the crucial design considerations include but not limited to the following: -

1. Tower Structure

The tower itself must be robust and stable-balance of forces during operation and idle times. Key factors include material strength, wind loads resistance and structural design. Common materials include reinforced concrete, steel or a hybrid structure.

2. Heliostat supports

The heliostats mirrors are mounted on supports which must withstand gravitational mass weights, thermal expansion, wind loads and possible seismic forces like earth quakes. Material selection and proper anchoring are critical –e.g. concrete pads embedded into the ground may act as resilient pivots for these structures.

Receiver Materials

The receiver atop the tower absorbs concentrated solar energy. It must withstand high temperatures and thermal cycling. A temperature of 565 O C gives effective thermodynamic efficiency needed for thermal energy storage and power generation.

Foundation Design

The tower's foundation ensures stability. Soil analysis, load-bearing capacity and seismic considerations influence foundation design.

Thermal Expansion

Tower components experience significant temperature variations. Proper expansion joints and material compatibility prevent structural damage.

Maintenance Accessibility

Design access points for maintenance and inspection. Safe walkways, platforms and service areas are essential.

Wind Loads

The tower and heliostats face wind forces. Aerodynamic design, wind testing and structural reinforcement address this challenge.

Lightning Protection

Towers are vulnerable to lightning strikes. We need to incorporate grounding systems and lightning rods for safety

Material Durability

Exposure to sunlight, heat and weather necessitates durable materials, coatings, corrosion-resistant alloys and protective layers enhance longevity.

Environmental Impact Assessment

The power plant will rob local societies of potential farming and mining land. Birds will hit or be killed by hot pipes and thermal energy storage tanks and receivers. The power station will disturb wild life ecosystems and displace habitats for wild life and birds in Kadoma. Spillage of molten salt may spoil the environment.

LAND AVAILABILITY AND LAYOUT

There is need for choosing an appropriate site and deciding on the layout of heliostats for efficiency and maximum impact. The site must ensure effective and efficient land use, energy collection and overall project feasibility.

Economic Viability

There is need for balancing capital costs, operational expenses and revenue generation which is crucial. The multi-tower design was avoided because of huge capital costs in favor of a single tower design. Cost effective designs and efficient operation contribute to project success.

Payback Period

It is important to note that the Central Receiver solar power plant offers promising potential for clean energy but addressing the above design considerations ensures optimal performance and long term viability. The penetration of solar power technology in Zimbabwe ensures clean and inexhaustible green energy on the Zimbabwean grid in accordance with world trends.

Environmental Impact Assessment

The 5 tower configuration consumes more geographical space which displaces mining and farming activities in Kadoma region. Birds may hit against the tower, solar absorber and tubes containing hot molten salt or water. Grazing land for wild life and domestic animals will be reduced. The habitat for certain wildlife will be reduced. As a result, a single tower Central Receiver Tower power plant is designed only.

Financial Feasibility

Funding constraints will be encountered by ZESA which may need forex from other entities within Mutapa group of companies like Kuvimba and the tax basket apart from loans from African Development Bank, World Bank and IMF. ZESA can also get foreign currency(forex) from exporting customers like mines and certain industries.

The thesis now proceeds to discuss future considerations

CHAPTER7

THE FUTURE

This project or design is done as part contribution and a step towards meeting currently existing gap in electricity supply and demand mismatch i.e. current electricity generation inadequacy. A power utility like ZESA in Zimbabwe needs to see 50 or even to 100 years' demand situation in its country in order to prepare for big projects in order to prevent fire-

fighting like the current situation in Zimbabwe. There are monthly load readings taken at all 33/11 KV substations which can be used in forecasting load whose National aggregate points to National generation requirements. Should ZESA decide to standardize on this design template and therefore replicate it in future, a load forecasting is required. In addition, load forecasting will be required to forecast the amount of sunshine or solar intensity radiation and therefore generation in a day, week, month or years' time from current. Therefore, a brief discussion of load forecasting methods will be covered in this thesis as follows:

Power System Planning and Load Forecasting Methodologies

Introduction

Load-forecasting skills are becoming more imperative because of increasing penetration of variable renewables into the grid. There is need to forecast both the variable weather, variable generation and variable load for short term, medium term and long term. Therefore, this paper attempts to share load forecasting methodologies suitable for short term, medium term and long term.

This section is an overview of load forecasting methodologies ventilated in current literature material. Renewable grids are unique in that both the demand and the generation which are highly intermittent and variable both have to be forecasted and matched. Therefore, forecasting skills are of paramount importance. The part of the project will appraise, analyze and highlight the strengths, shortcomings and weaknesses of each load forecasting methodology and whether it is suitable for extra-short term period forecasting (1 hour to 1 week), near term period/ or short term forecasting period (1 week to 1 year), medium term or intermediate period forecasting (1 year to 5 years), far term or long term period forecasting (5 years to 10 years) or super long term period planning (10 years to 20 years) The paper shall

also highlight those areas where the forecasts are used or purposes for such forecasts. This overview will also introduce key nomenclature in the load-forecasting and power system planning profession. Power system planning engineers are a type of profession that are included in the term ‘futurists’ in the social sciences as they mainly concentrate on the future domain for e.g. power utilities.

Contribution to the world body of knowledge will be proposed in terms of classifying forecasting and planning horizons into super near-term (1 minute to 1 hour), extra-near term (1hour to 1 week), near term (1 week to 1 year), medium/intermediate term (1 year to 5 years). far or long term (5 to 10 years), super far term (10 to 20 years) supra far term (20 to 50 years), centurio-term (50 to 100 years), millennium term (100 to 1000 years) and mega-term (1000 to 10^6 years) forecasting and planning horizons. Contribution to the world body of knowledge is also done by introducing the term electrical power cell which is a term introduced in the power system planning nomenclature which is a circle or sphere whose radius is the maximum length from a transformer within which technical specifications of the electricity supply is within permissible technical limits and beyond which technical limits begin to be violated if same size and type of conductors, feeders or distributors are used. It maybe any shape if different sizes and types of conductors are used.

The section posits that the load forecasting methodology adopted depends on the planning horizon which planning horizon depends on the uses to which the load forecasting is to be put to. Among the forecasting methods included in this paper includes fuzzy logic, artificial intelligence, Linear regression, time series linear regression, moving averages, floor space methods, end use energy methods and Model for Analysis of Energy Demand (MAED).

The part of the thesis also recommends areas for future research in load forecasting engineering and power system planning sciences especially when green energy and smart grids are being embraced world-wide as fashionable modernity in power systems.

The section is concluded by appealing to all engineers to continue for the search of other advanced and more accurate load forecasting methodologies using artificial intelligence, super sciences and cloud computing skills. Data sciences is also proposed as an area which can improve, enhance and revolutionize load forecasting accuracy. Historical data archiving and retrieval is also important if regression methods are to be accurate.

This part of the thesis concludes by recommending that the engineering family of professions should continue to advance knowledge frontiers in the areas of mathematics, statistics, electrical power engineering, control systems, digital communications, measurements and instrumentation which are key in power system planning sciences.

Main Narrative

Problem Statement

Future weather, grid-load-demand and future generation requirements need to be known in advance. Load forecasting is needed for power station operational planning and determining how many more power stations will be required in future-this is an area of complex sciences.

Research Questions

1. Can the value of a future variables such as weather, load demand or generation be determined?
2. What are the forecasting methods ventilated in literature?

Objectives

1. To determine the different types of forecasting methods.
2. To determine when each forecasting method is ideal.

The main objective of forecasting and planning is to ensure adequate, reliable, quality and delightful electricity supply to end users who are normally customers, consumers or stakeholders and safety to all staff and members of the public. A quality electricity supply meets the needs of various customers and is calculated to satisfy or even delight stakeholders. The designed power station must be constructed, maintained and operated in order to meet the above requirements.

A quality electricity supply according to T.P. Munyanduri (1999), has no or has the following parameters within acceptable limits: - harmonics, voltage flicker, voltage dips, outages, no interference to neighboring electrical and communication systems, voltage imbalance and voltage regulation

A quality electricity supply has the following: - i.e. 100 % supply continuity and reliability, acceptable voltage profiles, constant supply frequency, pure sinusoidal voltage and current waveforms, safe to personnel, equipment and environment,

equal peak voltages in each phase of a three phase supply and fixed angles of 120° between phases

In practical supply systems, supply quality disturbances are caused by the following events which include lightning, trees falling on power lines, switching on and off large loads e.g. starting and stopping large motors-switching surges, system faults, switching of certain circuit elements such as capacitor banks, old aged equipment, reptiles creating short-circuits and veld fires.

.

Waveform distortions are caused by non-linear loads such as rectifier converters, variable speed motor drives, static var compensators, HVDC links, electric arc furnaces and welding machines.

Power system planning should foresee all the above and protect against them in the design. Planning is a highly essential, vital and very important activity for any power utility or any engineering project implementer. Without proper planning any engineering company, power utilities included will experience surprises, shocks and will always be in a firefighting mode! The key and essential component of planning is load-forecasting. Forecasting is like the windscreen of a moving vehicle which enables the driver to see the road ahead and therefore timeously scheme current and future actions that need to be done to avert disaster! Without planning engineers will always be in reactive mode rather than being proactive!

Load forecasting is essential for (1) efficient and economic system operations e.g. efficient and effective power dispatch among feeders (2) optimal power system planning and (3) maintenance scheduling and (4) power station fuel procurement scheduling e.g. coal procurement.

Definitions

A plan: Is a chronological list of actions, activities, projects to be implemented and or work that must be executed or done in series or parallel by one person or a team of people, machines or animals now and in future in order to realize a desirable future, obtain desirable future results or achieve quality supply in defined areas of interest. A methodology of achieving the future we want or a scheme of future actions (T.P. Munyanduri, 2020).

Power System Planning: is the activity involving identifying plus documenting all future projects to be carried out within an electrical network or grid in order for the power system to be able to competently and decisively convey electricity within permissible technical limits of voltage, frequency, harmonics, voltage flicker, voltage dip and appropriate current levels from power generation units or supply buses to fully meet future demand and guarantee quality supply within a defined geographical area during the considered forecasting and planning horizon. It is the process of visualizing, conceiving, forecasting or foreseeing the future and then subsequently listing all activities in chronological order in series or in parallel that needs to be done or implemented in order to realize a highly desirable future and guarantee quality electricity supply. It is the process of creating a roadmap into a desirable future in terms of a power system expansion plan and strategy (T.P. Munyanduri, 2020).

Forecasting: Prediction of a future variable e.g. weather, generation or load

CLASSIFICATION OF PLANNING HORIZONS

Most literature including Xiaobin (2017), P. Ganguly, A. Kalam and A. Zayegh(2017), D. Ali, M. Yohanna, M.I Puwu and B.M. Garkida(2016) classify planning horizons for power systems into only three categories i.e short-term, medium term and long term which this author would like to call **near horizon** planning(**nearizon** planning), **average horizon** planning(**averizon** planning) and **far horizon** planning(**farizon** planning) respectively. The bold and underlined words are hybrid words (one word created from two words e.g. (**near horizon-nearizon**), (**average horizon-averizon**)). This is contribution to world body of knowledge. This author would like to classify forecasting and planning horizons into nine planning horizons as part of contribution to the world body of knowledge. Extra-near period (or **extra nearizon**) planning involves a planning horizon of 1hour to 1 week. near period (**nearizon**) planning involves forecasting and planning for 1 week to 1 year. average term(**averizon**) planning foresees 1 year to 5 years whereas far term/time(**farizon**) planning scans a period of 5 years to 10 years. Extra-far period (**extra farizon**) planning forecasts and plans for 10 to 20 years. Super far (**super farizon**) term planning has a planning horizon of 20 to 50 years. **Centurio-planning** involves 50-100 years. **Kilo term** planning involves 100-1000 years and **Mega-term** planning 100-10⁶ years.

The author substituted short term (with near horizon), medium term (with average horizon) and long term with far horizon) which are more appropriate and accurate terms in what we are describing in the forecasting and planning profession as contribution to world body of knowledge.

INTRODUCTION

Planning is an essential, vital and important engineering skill. It is said, 'Any road is right, provided you do not know where you are going'. Forecasting enables us to comprehend where we are going in terms of weather, production, load or demand as a power utility. Generation needs to track demand.

As mentioned before short term planning (nearizon planning) is done for planning operations i.e. planning supply, electricity or energy dispatch over a short time horizon from power stations, transmission lines and distribution networks including power imports normally done from the National Control Centres of power utilities. It is also important for scheduling generation i.e. unit commitment and determining spinning reserve.

Medium term planning (Medizon planning) is done for planning maintenance work i.e. for maintenance scheduling e.g. for substations, lines,

Long term planning (farizon planning) is done for power station maintenance, including transmission substations. It is also done for determining system additions and network expansion plans i.e. new power station requirements.

Extra-long term planning and above are done for power station, transmission and distribution equipment sizing-i.e. capacity planning.

Load-forecasting methodologies include regression, moving averages, graphical trend-extrapolation method, appliance saturation, floor space including fuzzy logic, artificial neural networks which may be used for short-term load prediction.

Short term load forecasts are done in order to optimize system operation, to enhance efficient load dispatch, determine plant unit commitment and for scheduling power imports and exports to neighboring utilities as well as determining the needed spinning reserve.

Medium term forecasts are used for scheduling maintenance activities on power system equipment such as power stations, transformers, generators, breakers etc.

A power system study, network analysis and long term load forecast is done for a power utility in order to identify needed system additions and to craft, formulate and design a power system expansion plan as well as design grid intelligence in the form of condition monitoring equipment and protection.

Demand forecasting or load forecasting in quantity or magnitude as well as in geographical spread is the first step in any power system planning process. The sizing and specification of power stations, substations, transformers, breakers, CTs, VTs, feeders and distributors for the distribution network follows from the localized demand forecasts. Load-flow studies maybe done to determine e.g. short circuit currents that the breakers are supposed to interrupt. Grid intelligence (i.e. Over-voltage, over-current, differential and earth fault protection design then follows). Budgeting and scheduling of projects is the final step. Manpower planning for implementing projects cannot be efficiently done without an accurate load forecast and therefore power system planning. Transport requirements to implement those projects then follows.

For short term planning meteorological data is sorted in order to predict the weather for weather sensitive load. For similar day method, data from National control centres is also compiled.

For long term forecasts load-readings are taken from each 33/11 kv, 132/33 kv and 330/132 kv substations e.g. by power utility electricians every months and submitted to the planning office as well as operations for long term forecasts and for the maintenance office. It is these load-readings that are used for demand forecasting together with municipal and rural council commercial, residential, industrial, mining and farming development plans for distribution planning. Regression analysis using annual maximum demands substation by substation is then employed

Case study forecasting such as appliance saturation method, floor-space methods, fuzzy logic, neural networks will not be discussed in this section.

DIFFERENT LOAD FORECASTING METHODS

(Uday Patel, 2021), articulates the point that load forecasting methods include: - Correlation method, Univariate Model Method, Similar Day Method, Hierarchical Forecasting Method, Time Series Method (moving averages (trend average of points), Least Squares), Expert system method (weighted averages), Artificial neural networks method, Fuzzy logic and Linear Regression method. There is also Model for Analysis of Energy Demand(MAED) method, floor-space method and end use energy methods

This author would like to also include graphical trend extrapolation method, appliance saturation method and floor-space method.

The simplest method of forecasting is to simply and graphically extrapolate the historical demand curve trend into the future using annual peak demand plotted against years of operation. This can alternatively be done mathematically by using regression.

(Uppal and Rao, 2015) posits that analytical functions which can be used for determining the trend curve include, Straight line $y=a+bx$, Parabola $y=a+bx+cx^2$, S-curve $y=a+bx+cx^2+dx^3$, Exponential $y=ce^{dx}$ and Gampertz $\log_e y=a+ce^{dx}$.

Where y =annual peak demand and x =time in years

The trend extrapolation method is used for long term planning when e.g. 10 years of historical data (annual peak demands) are available for extrapolating for the next 10 years, 20 years for future 20 years etc. Missing data on historical data maybe estimated by moving averages method.

Linear Regression Method

(M.D. Reddy, N. Vishali and Pulivendula, 2017) says that it is a statistical method employed for determining the relationship between two or more variables (e.g. population growth rate and load). If the relationship is found it is named or termed, 'Simple Linear regression'. If we identify the relationship between more than two variables (e.g. demand and population growth rate, GDP per capita), then it is called multivariable linear regression.

Linear regression assumes the configuration $y=mx+c$ where m is the gradient whilst c being the intercept constant. Constants m and c can be calculated using historical data of y and x . The variable y is the dependent variable whilst x being the independent variable.

This method assumes that past and present trends will persist into the future! The main disadvantage of this method is that if future trends deviate from past and present trends false results are obtained e.g., the corona virus resulted in the closure of many non-essential industries and energy demand plummeted. The land reform in Zimbabwe where farms belonging whites were invaded by blacks who had no experience in irrigation farming led to massive decline in energy demand in farming areas and past trends were no longer valid. If there is a sudden outbreak of war like in Ukraine, industrial and commercial infrastructure may be destroyed and past trends may not be good predictors of future demand.

Time Series Linear Regression

(M.D Reddy, N. Vishali and Pulivendula, 2017), alleges that two specifically known variables are involved in the normal linear regression, whereby time is adopted as one of the variables in the Time Series Linear Regression (e.g. load(y) as a function of year(x) with the initial year taken as 1). Annual Maximum Demands(MDs) are taken every year and then MDs are taken as y and year as x. This method has been used extensively for long term electricity demand forecasts in the Zimbabwe Electricity Transmission and Distribution Company(ZETDC) Northern Region. Only one variable is known specifically i.e. MD.

This method has the same disadvantages as the Linear regression in that it assumes that past and present trends will persist into the future. If future trends defer from previous trends, the method may give false results.

Correlation method

Demographic and economic variables like population growth rate, building permits, equipment saturation and weather data which are positively correlated with demand are used for forecasting future demand. This method except weather data may be used for long term forecasting. Weather data is used for short term planning. The main disadvantage of this method is that if the correlation coefficients are calculated wrongly false results may occur. It depends on the accuracy of the correlation coefficients.

Similar Day Approach Method

Similar day of the week, similar seasons of the year with similar weather normally have same demand profiles! This observation becomes the basis of forecasting future load and future demand. This forecasting method is normally used for short and medium term planning. This method assumes that similar days will result in identical or similar demand. This may not be the case leading to wrong forecasts.

Neural Network Forecasting

(Shmueli, 2012) posits that neural nets are data-driven machines with learning algorithms. They capture relationships between inputs and output variables. This method is normally used for short term forecasting. Neural networks have input layer(neurons), hidden layer and output layer(neurons). Connection or links between neurons have weights. Learning, training and back-propagation may be used for forecasting.

Fuzzy Logic

(D. Ali, et al. 2016) highlights that Crisp data of historical weather affecting parameters (e.g. temperature, wind speed, rainfall and humidity) and load are assigned membership of fuzzy sets using Fuzzification. They are inputted into a fuzzy inference engine which uses the IF-THEN functions. The output is a load forecast which must be converted from fuzzy into crisp data using defuzzification process. Fuzzy logic is normally used for short term load forecasting.

The Energy method of Forecasting

Annual electricity sales to different customer categories e.g. residential, mining, farming, commercial and industry is forecasted using historical data and then use the annual load factor to convert this kWhr sales to annual peak demand. This method is normally used for long term.

APPLIANCE SATURATION METHOD

This method is normally used when planning electricity reticulations for new residential, industrial and mining complexes. You first take an audit of all the appliances or equipment total wattage ratings from the name plates to be installed in a single typical house, mine or industry. Since all equipment in a single house or industry are not going to be on at the same time, you divide this total wattage with a diversity factor (or multiply by the simultaneity/coincidence factor.) to get a typical load per house or industry or mine. You multiply this total wattage after dividing by diversity factor per unit by the total number of houses or industries or mines to get the aggregated or compound demand on the grid. You decide on the sizes of transformers to be used. You then divide the aggregated demand by the size of a single transformer to get the number of substations required. You then position these substations with these standard transformers on load-centres. Then you design your feeders.

FLOOR SPACE METHOD

This method is used to forecast the amount of lighting tube/and or bulbs and therefore energy requirements needs in rooms of houses or high rise buildings. From the wattage on the bulb you can calculate the luminance levels/brightness per square meter. There are standard luminance levels recommended per square meters. From the area of the room and luminance per bulb, you can calculate the number of bulbs or globes required for optimal lighting. The author used this method when he was working for the Ministry of Public Construction and National Housing in Zimbabwe.

IMPORTANCE OF LOAD FORECASTING

Load forecasting is used to determine future demand in order to plan for network additions and to come up with system expansion plans-i.e. future capacity planning. It is also used to determine future fuel requirements e.g. for power stations coal, natural gas, oil, solar energy etc. Load forecasts are further used to optimally operate the system-operations planning e.g. for power utilities and also to enable equipment maintenance to be done economically and when load and demand are minimal i.e.

maintenance scheduling. They are also used to enable power purchase agreements to be made and signed with a measure of confidence. Interconnectors between neighboring utilities e.g. from different countries are constructed to defer investment in expensive generation. The last and most important purpose of a load forecast is to increase the safety and reliability of a power system.

(Patel, 2021), highlights that the factors which affect load include: -

Weather, economic development, special events, life styles, power tariffs, population growth, season, day of week and season of year. (Pradnya Patkar, 2022) says that weather is the most significant factor affecting load forecasting-i.e. extra-short-term and short term forecasting. Weather affects the reliability of a power supply. (Patkar, 2022) demonstrates that temperature, humidity, precipitation, wind speed, wind direction, cloud cover and light intensity affect demand for electricity

When planning, we talk about signals and systems. For power utilities the signal is electricity and the system will be the electricity grid or electricity network/circuits. The signal should be able to flow within the system safely without overload on any component of the electricity grid with minimal losses, deterioration or distortion of the signal. There are 2 types of signals which we can talk about. Analog signal and digital signals! The methodology of planning for these two types of signals differ. Digital circuits are normally built with the transistor as the building block and analog circuits are the normal RLC circuits for ac and d.c. Digital circuits are planned for only two types of signals normally 1(5V) and zero '0'(0V). Power system planning is analog signal system planning which is the focus of this paper. Digital circuit planning is reserved for future journal publication.

Planning for power utilities or power system planning involves demand forecasting, distribution planning, sub-transmission planning, transmission planning and lastly generation planning. These activities feed into each other in the order given.

The power utility activity cycle involves

Planning (load-forecasting, design, costing, timing) Resources Mobilization Project Implementation Monitoring and Control Network-Performance Evaluation Performance Gap identification

Grid and network planning for a power utility generally and normally involves plans for medium voltage(MV), high voltage (HV, extra-high voltage (EHV) and ultra-high voltage (UHV) lines, cables, power stations and substations including condition monitoring and protection systems (grid intelligence).

PURPOSE OF LOAD-FORECASTING

Load forecasting is carried out in order to enable proper planning of the power system, scheduling of developmental plans, planning of distribution, transmission and generation equipment, efficient and effective grid/network electricity generation scheduling, manpower needs, financial disbursement planning, grid configuration and energy sales plans, plant sizing and to determine location of generation facilities.

Grid network intelligence planning normally involves planning for protection, condition monitoring, generation control, transmission and distribution control which are plans normally involving extra-low voltage(ELV) and their interfaces with the power network through items such as breakers, CTs, VTs and other transducers and sensors.

After the demand forecast, six fundamental questions need to be answered. The first question is, is the distribution infrastructure adequate to accommodate the extra load identified by the forecast taking geographical and network topology into consideration? The second question is considering transmission lines feeding nearest bulk supply substations, is the feeding transmission infrastructure adequate to accommodate the extra load identified by the forecast? The third question is and if so, is the generation and interconnector infrastructure adequate to accommodate the extra load identified by the demand forecast together with estimated technical losses? The fourth question is and if so, are the new network and business expansion plans addressing modernity? The fifth question is are the human resources, material resources, transport and facilities(buildings) sufficient to support new network and business expansion plans? The sixth question is after costing the above needed resources, are the financial resources adequate to finance the network and business expansion plans?

Electrical energy cannot economically be stored and therefore the right quantity of energy/electricity must be dispatched to the right place and simultaneously at the right time when needed. The danger of supply inadequacy can be enumerated by the chances/probability that generation will not meet peak demand. This is termed or called 'Loss of Load Probability (LOLP)'. Typically, the acceptable LOLP is about or below 10 %L.

Equipment Sizing Planning Sequence

Distribution Load-forecasts and distribution and Transmission losses

Transmission network → Generation plants and interconnector design.

$G = SR + TL + DL + D$ Equation 2.1 (Used for generation forecasting)

Where

G= generation

SR=Spinning Reserve

TL=Transmission technical losses

DL-Distribution technical losses

D=Demand (actual load plus unsatisfied demand)

AL=Actual satisfied load

$D = AL + UD$

Where

D=Demand

AL=Actual load

UD=Unsatisfied demand

$T=TL+DL+AD$ Equation 2.2. (Used for transmission forecasting)

Where T =Transmission load

$DTN=DL+ D$ (Used for Distribution load forecasting)

DTN =Distribution

The distribution load-forecast plus about 10% technical losses gives us an idea of sizing of the transmission network. The transmission network size= (distribution load-forecast plus distribution and transmission losses). Generation sizing =distribution load forecasts plus about 10% distribution technical losses plus about 10% transmission losses plus generation losses)

Generation Planning

(S.L. Uppal and S. Rao, 2015), posits that sources of energy include the Fissile materials e.g. uranium, plutonium and thorium; Fossil fuels which include natural gas, coal, and oil; Hydro generation-i.e. dammed water; Wind; Tidal; Wave and Solar. The author would also want to add thermoelectricity, piezoelectric, magneto hydrodynamic, thermionic generation, greenhouse-chimney generation, Photo-voltaic solar and Concentrated Solar Power plants.

In generation planning, we have to decide which energy sources we will construct, commission, operate and connect to the grid! We look at the economics, technical feasibility, safety and environment impact before selecting an appropriate generation method.

(S.L. Uppal and S. Rao, 2015) highlights that **spinning reserve** is the generating capacity in excess of the actual loading of the committed units.

(S.L. Uppal and S. Rao, 2015) further says that the demand(D) of an area at any given instant consists of the following components: -

$D=L+W+C$

Where

L=base load

W=is the weather dependent component

C= the part which is due to some festival or event

(S.L. Uppal and S. Rao, 2015) alleges that **base load** is the portion of the demand which is dependent on the overall economic activities and the general climatic condition of an area.

The installed generation capacity need to be greater than expected peak demand!

Peak demand plus transmission and distribution losses =generation

For generation, transmission and distribution planning, we normally plan for peak load.

(Weedy, Covy, Jenkins, Ekanayake and Strbac, 2012), posits that production capacity available minus peak load=capacity margin. Previous experience has shown that adequate generation security needs a capacity margin of around 20 %. In case that the peak demand exceeds generation that demand need to be reduced e.g. by load-shedding.

FACTORS AFFECTING DEMAND INCREASE

Demand is affected by population growth, growth per capita, weather, time of day, day of week and season of year; increase in appliance ownership by residential customers or electrical equipment increase by industrial, mining and commercial customers; residential expansion, industrial, mining, commercial and farming expansion within a geographical area.

(Pradnya Patkar, 2022) says that electrification is increasing because of increase in population. The population and so demand is increasing while traditional sources of

energy like coal, natural gas and oil are getting depleted. (Pradnya Patkar, 2022) posits that power system expansion planning starts by the process of load forecasting. We normally use historical data to predict future load needs. Predictions of future electricity and energy demand are important, necessary and vital for enhanced and competent planning. Network/grid expansions and system additions are determined from extra-long term load forecasts.

The term planning is inclusive of load forecasting, design, budgeting and project scheduling. In the design process all customers must fall within cells of transformers and generators for given sizes of feeders and distributors for quality electricity supply.

Technical, environmental, financial and economic appraisals of projects are part of the planning process done in power utilities.

AREAS FOR FUTURE RESEARCH IN THE LOAD FORECASTING AND POWER SYSTEM PLANNING SCIENCES

The green energy revolution and the era of smart grids calls for advanced grid and network intelligence in the form of enhanced condition monitoring equipment and advanced protection. The electrical network should be able to handle fluctuating energy flows such that signals (i.e. sinusoidal electricity) should be transmitted safely without exceeding insulation breakdown strength of grid components. Data sciences will improve load forecasting skills.

SPESTECH CRITERION (Spiritual, Political, Economic, Social, Technological, Ecological (Environmental, Competitive, Healthiness) Appraisals)

The SPESTECH criterion is also referred to as a 360^o planning. Criterion. There may be spiritual, political, economic, social, technological or environmental factors that may act against the best interest of the project which need to be eliminated.

Any project has to satisfy each and every one of the above criterion for project ideality and also to achieve superiority from the perspective of all stakeholders.

Renewables are there to satisfy the Healthiness criterion on the medium term to long term perspective.

For Example, in China where the top 6 within the Chinese Communist political party are all engineers, the environment for project implementation is better than in the USA where the top two are lawyers or in Zimbabwe where the all Presidents from 1980 to now are lawyers, In Zimbabwe from 1890 to now all Prime Ministers and Presidents where from the Arts class. These are political dynamics which can facilitate or inhibit project implementation! In a mainly Moslem/Christian world there may be need to balance the belief perspective of all religions with the Almighty God, the most Merciful, the Most Compassionate being the supreme pinnacle in the religious belief value system! Heresy against the most Holy is to be eliminated at all cost.

LOAD-FORECASTING CONCLUSION

Load-predictions are the first prerequisite for competent network/grid component and configuration planning, efficient and economic system operations. Load-forecasting is the prediction of future demand on the grid and electrical network. There are various load-forecasting techniques depending on whether we are concerned with system operations, maintenance scheduling or network additions and grid or network expansion plans. Fuzzy logic, similar day of the week and artificial neural networks are for short term forecasting (hours to weeks). These load forecasting techniques are done in order to enhance system operations normally for the National Control centres for power utilities. Similar day of the week is used for medium term load forecasting (weeks to a year) which is normally done for maintenance scheduling of the power system equipment. Regression, the method of Least squares and time series including moving averages is done for long term load forecasting which is done for network expansion plans including new generation requirements. Equipment saturation or appliance saturation method is used for load forecasting for new system additions and the floor space method is used for load forecasting in buildings e.g. commercial buildings. Fuzzy logic is normally done for short term forecasting.

After load forecasting, power system planning is then undertaken. Network expansion designs and equipment sizing then becomes possible. Least cost planning is done after technical, economic and financial appraisals.

The design part of planning requires advanced knowledge in electrical power engineering, mathematics, statistics, control systems, instrumentation and measurements as well as digital communications. Engineers should continue researching on new, advanced and more accurate forecasting methods in order to improve the planning process which is key and core to superior electrical supply to customers.

Once a power utility like ZESA decides on the implementation of this project design, load forecasts will determine how many such power stations need to be replicated in the country to satisfy such future demand.

The project now proceeds to draw conclusions, identify areas for future research and make recommendations.

COMPUTER SIMULATIONS

This section simulates design using Matlab and Matlab Simulink to confirm results done using manual calculations. It starts by simulating the heliostat solar field, then storage tank, then heat exchanger, then height of tower and lastly simulation for the whole plant.

% Heliostat Field Design programme

% MATLAB Program to calculate heliostat mirror requirements

% Given Output Power

Po = 500e6; % 500 MW converted to Watts

% Efficiency (Output is 20% of Input)

efficiency = 0.20;

% (1) Calculate Input Power (Pi)

Pi = Po / efficiency; % in Watts

fprintf('Input Power (Pi) required: %.2f MW\n', Pi / 1e6);

% (2) Solar radiation intensity

solar_radiation = 500; % W/m^2

% Area required without shading and blocking allowance

Ar = Pi / solar_radiation; % in m^2

```
fprintf('Area required without shading allowance (Ar): %.2f m^2\n', Ar);
```

```
% Total area required with 25% extra for shading and blocking
```

```
total_area = 1.25 * Ar;
```

```
fprintf('Total area required including shading and blocking: %.2f m^2\n', total_area);
```

```
% (3) Mirror specifications
```

```
mirror_area = 140; % m^2 per mirror
```

```
% Number of mirrors required (based on Ar, not total_area)
```

```
Mr = Ar / mirror_area;
```

```
fprintf('Number of mirrors required (Mr): %.0f\n', ceil(Mr)); % rounded up
```

```
MATLAB DriveField.m
% Matlab Program for Designing Heliostat Field

% Given Output Power
Po=500e6; % 500 MW Converted to Watts

% Efficiency (Output is 20% of Input)
efficiency=0.2;

% Calculate Input Power (Pi)
Pi=Po/efficiency; % in Watts

% (2) Solar radiation intensity
solar_radiation=500; % W/m^2

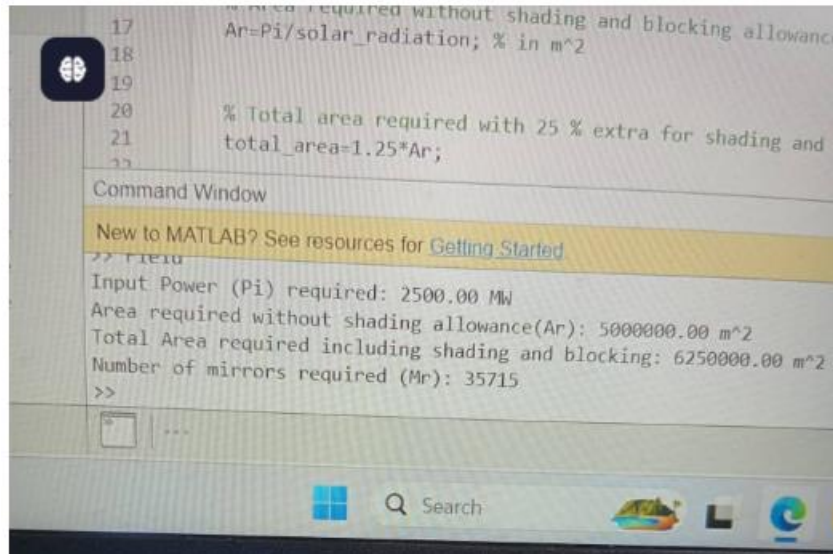
% Area required without shading and blocking allowance
Ar=Pi/solar_radiation; % in m^2

% Total area required with 25 % extra for shading and blocking
total_area=1.25*Ar;
```

Command Window

new to MATLAB? See resources for [Getting Started](#).

Input Power (Pi) required: 2500.00 MW
Area required without shading allowance(Ar): 5000000.00 m^2
Total Area required including shading and blocking: 6250000.00 m^2
Number of mirrors required (Mr): 35715



The simulation gives Input Power= 2 500 MW

Area Required without shading and Blocking=5 000 000m²

Total area required including shading and blocking efficiency=6 250 000

Number of Mirrors=35 715

% Matlab Programme for plotting graph of Sunlight Power Input into the Heliostat
 % Mirrors versus time from morning(06:00 a.m.) to noon (12:00) to evening (18:00
 % p.m.)

% Define time in hours

t = linspace(6, 18, 1000); % from 6 to 18 in 1000 points

% Map time to a half-sine from 0 to π :

% t = 6 $\rightarrow$ angle = 0, t = 12 $\rightarrow$ angle = $\pi/2$, t = 18 $\rightarrow$ angle = π

theta = (t - 6) * (pi / 12);

```

% Compute half-sine wave, scaled to peak at 2500 MW

y = 2500 * sin(theta);

% Make sure endpoints are exactly zero (numerical safety)

y(1) = 0;

y(end) = 0;

% Plot

figure;

plot(t, y, 'LineWidth', 2);

xlabel('Time (hours)');

ylabel('Power (MW)');

title('Electrical Power Generation Curve: 0 MW at 06:00, peak 2500 MW at 12:00, 0 MW at 18:00');

grid on;

```

```

>> t=linspace(6,18,100);
>> theta=([t-6]/12)*pi;
>> power=2500*sin(theta);
>> plot(t, power);
>> xlabel('Time (HRS)');
>> ylabel('Power Generated (MW)');
>> title('Electrical Power Generation Curve ');
>> xticks([6 9 12 15 18]);
>> xticklabels(['0600', '0900', '1200', '1500', '1800']);
>> grid on;

```

10:40 am

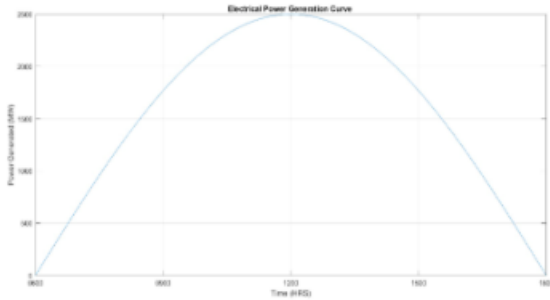
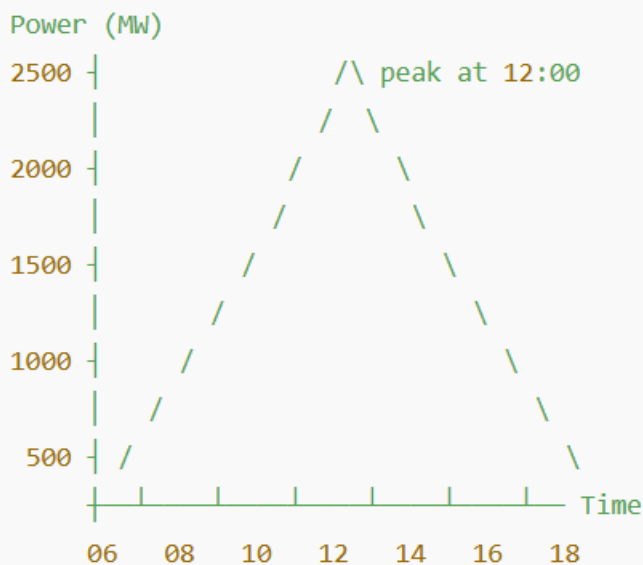


Figure 211 Matlab simulation graph of Sunlight Power Input to Heliostat Mirrors. At 06:00 there is zero output which peaks at 2500 MW at 12:00 afternoon and gets to zero at 18:00 p.m.

Rough ASCII Plot

yaml



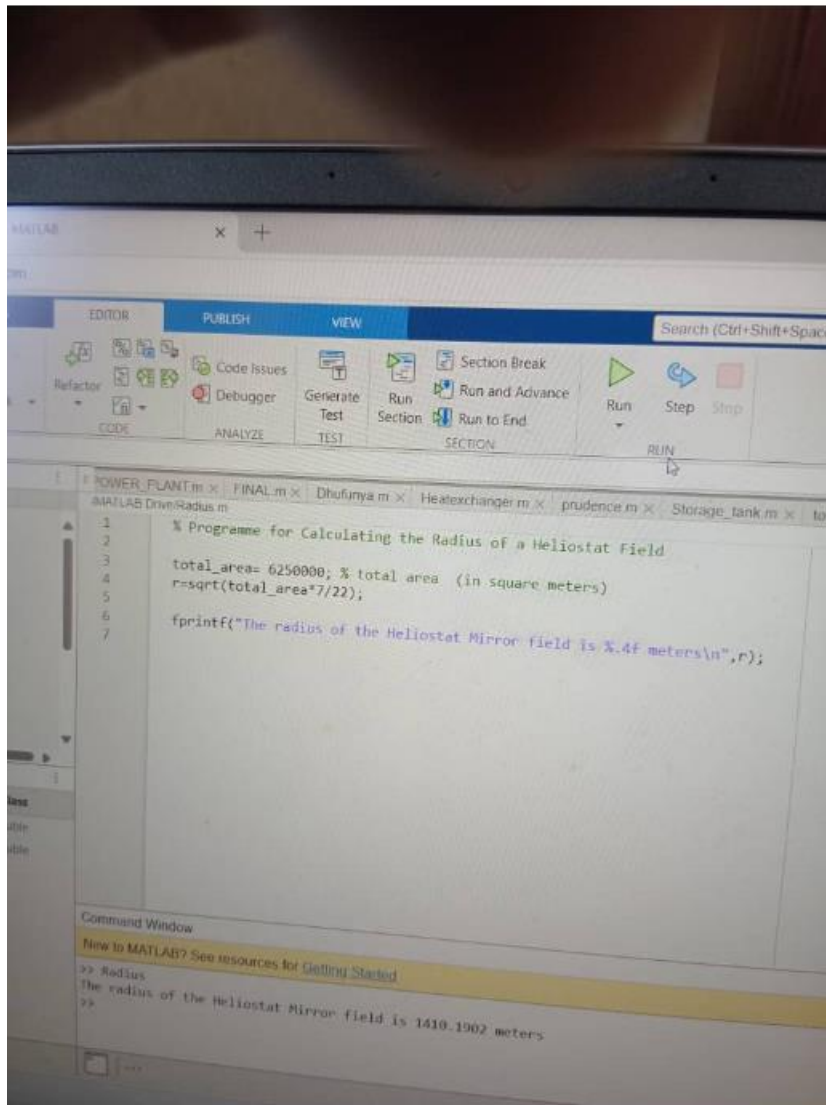
A rough simulation graph showing maximum sunlight power into the heliostat mirrors at 12:00 and zero at sunrise (06:00) and sunset 18:00.

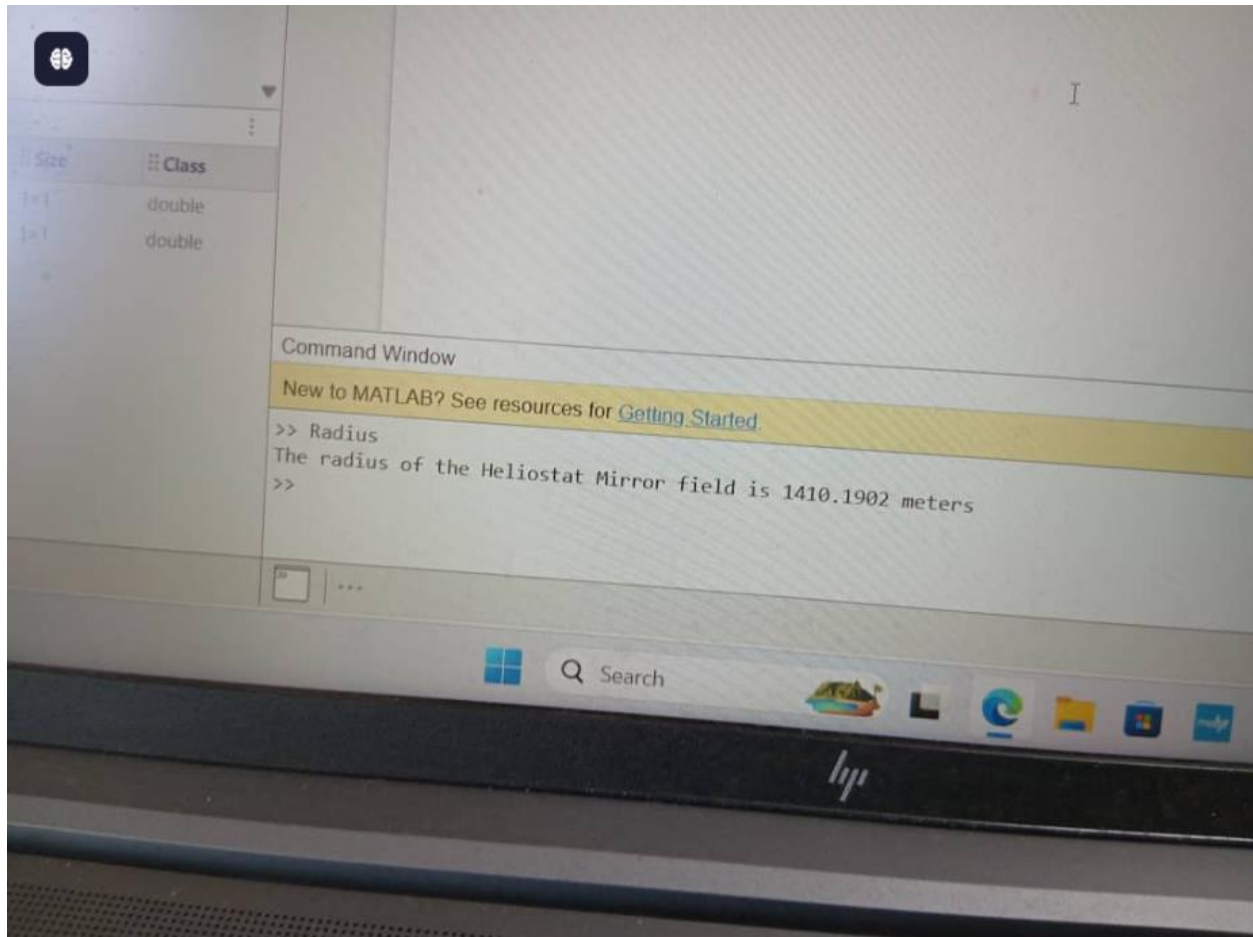
% MATLAB script to compute heliostat field radius

```
total_area = 6250000;    % total area (e.g. in square-meters)
```

```
r = sqrt(total_area * 7 / 22);
```

```
fprintf('The radius r of the heliostat mirror field is %.4f units\n', r);
```





The simulated radius= 1 410 meters

COMPUTER SIMULATION FOR STORAGE TANK USING SODIUM NITRATE ASSUMING A 10m High TANK

% Given values For Calculating the radius of Thermal Energy Storage Tank using sodium nitrate Assuming Tank 10 m High

c = 1371; % J/(kg·K)

```
d = 2260;      % kg/m^3
dT = 545;      % K (≈°C difference)
Q = 5e8;       % Joules (total energy storage)
```

```
% 1. Compute mass m (kg)
```

```
m = Q / (c * dT);
```

```
% 2. Compute volume V (m^3)
```

```
V = m / d;
```

```
% 3. Compute radius (m)
```

```
% Provided formula: radius = sqrt( (V * 7) / (22 * 10) )
```

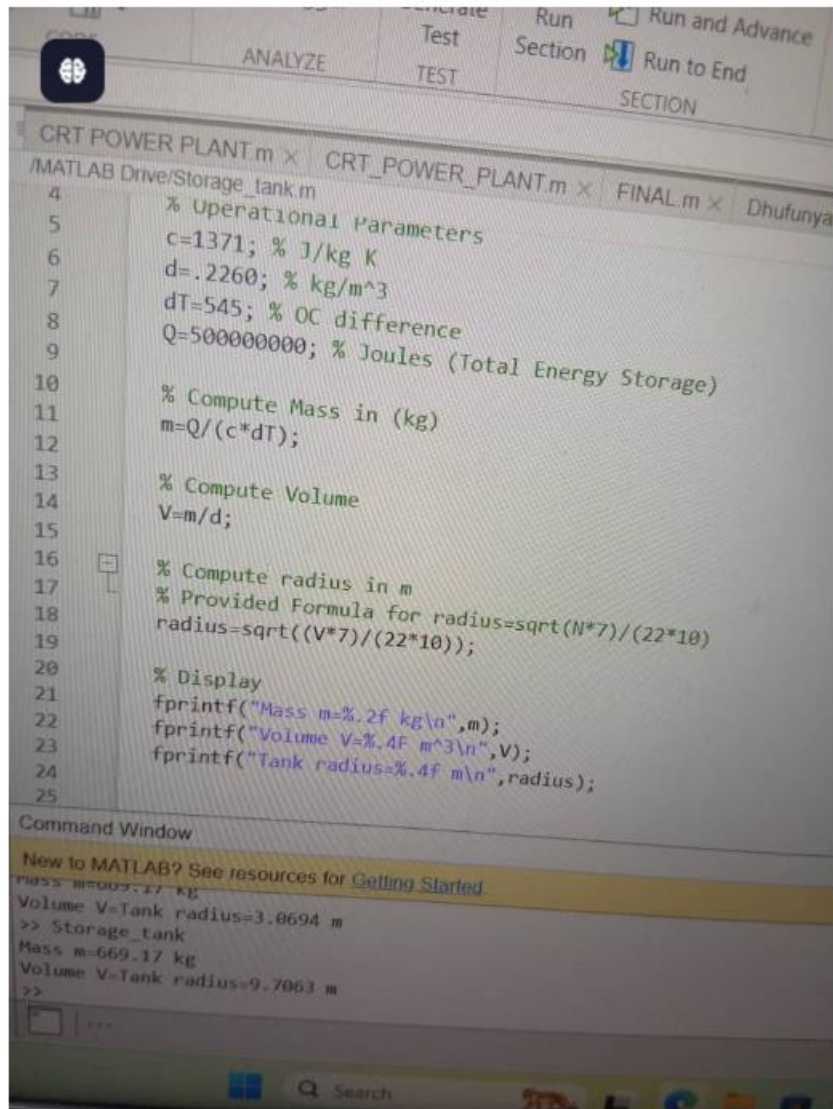
```
radius = sqrt( (V * 7) / (22 * 10) );
```

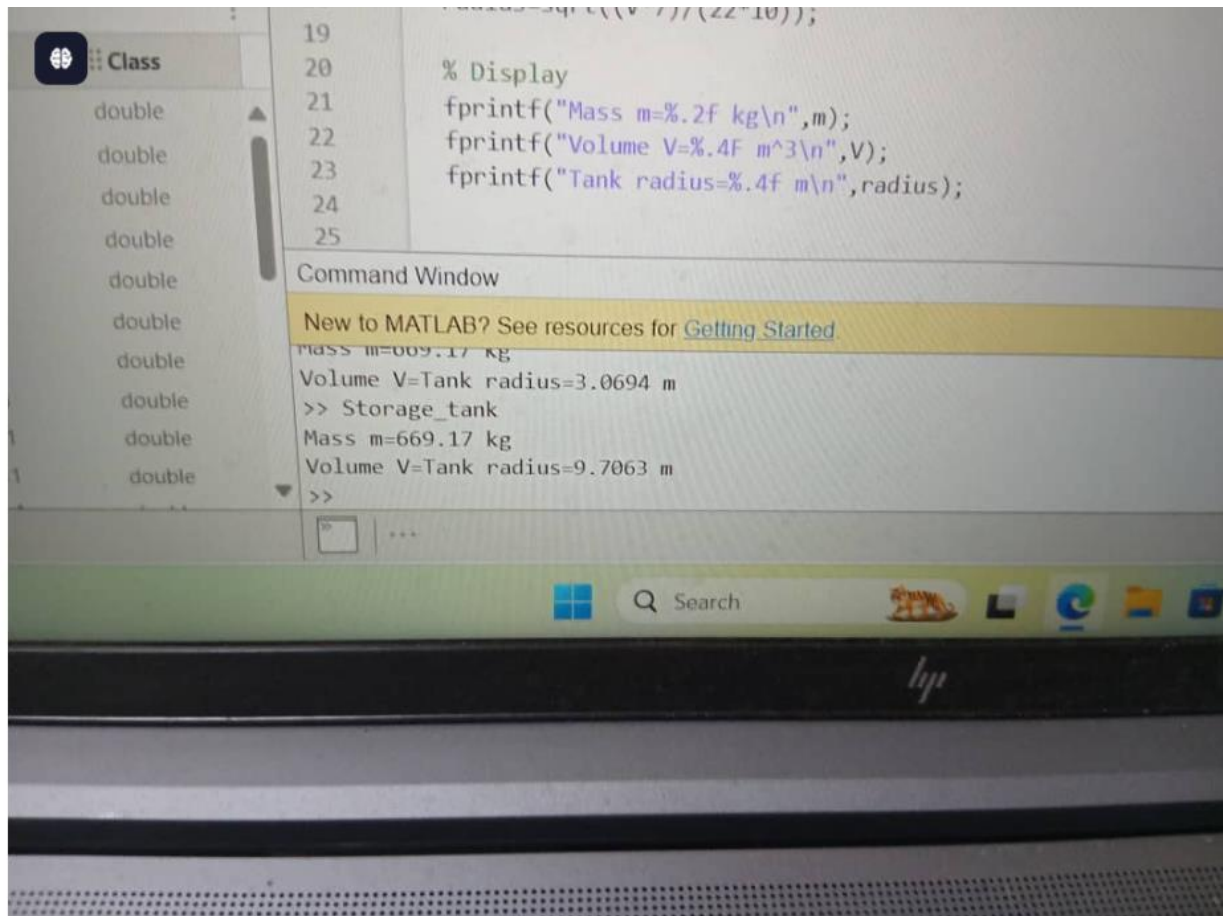
```
% Display
```

```
fprintf('Mass m = %.2f kg\n', m);
```

```
fprintf('Volume V = %.4f m^3\n', V);
```

```
fprintf('Tank radius = %.4f m\n', radius);
```





The tank has a radius =9.7m i.e. a diameter of about 20 m

SIMULATING PROGRAM FOR DIMENSIONING A HEAT EXCHANGER

% Given constants

cp = 1.118; % KNO3 specific heat capacity [kJ/(kg·K)]

cw = 4.25; % water specific heat capacity [kJ/(kg·K)]

dp = 2.11e3; % KNO3 density [kg/m^3]

dw = 1e3; % water density [kg/m^3]

Tfactor = 545; % temperature difference used in your energy balances

% Energy balances

% mw * cw * Tfactor = 500,000,000

% mp * cp * Tfactor = 500,000,000

mw = 500e6 / (cw * Tfactor); % mass of water [kg]

mp = 500e6 / (cp * Tfactor); % mass of KNO3 [kg]

% Volumes

$V_p = m_p / d_p$; % volume of KNO₃ [m³]

$V_w = m_w / d_w$; % volume of water [m³]

% Total volume

$V_{tot} = V_p + V_w$;

% Radius of heat exchanger (formula given: $r = \sqrt{(V_{tot} \cdot 7 / (22 \cdot 10))}$)

$r = \sqrt{V_{tot} \cdot 7 / (22 \cdot 10)}$; % radius [m]

% Display results

fprintf('Mass of KNO₃, $m_p =$ %.3e kg\n', m_p);

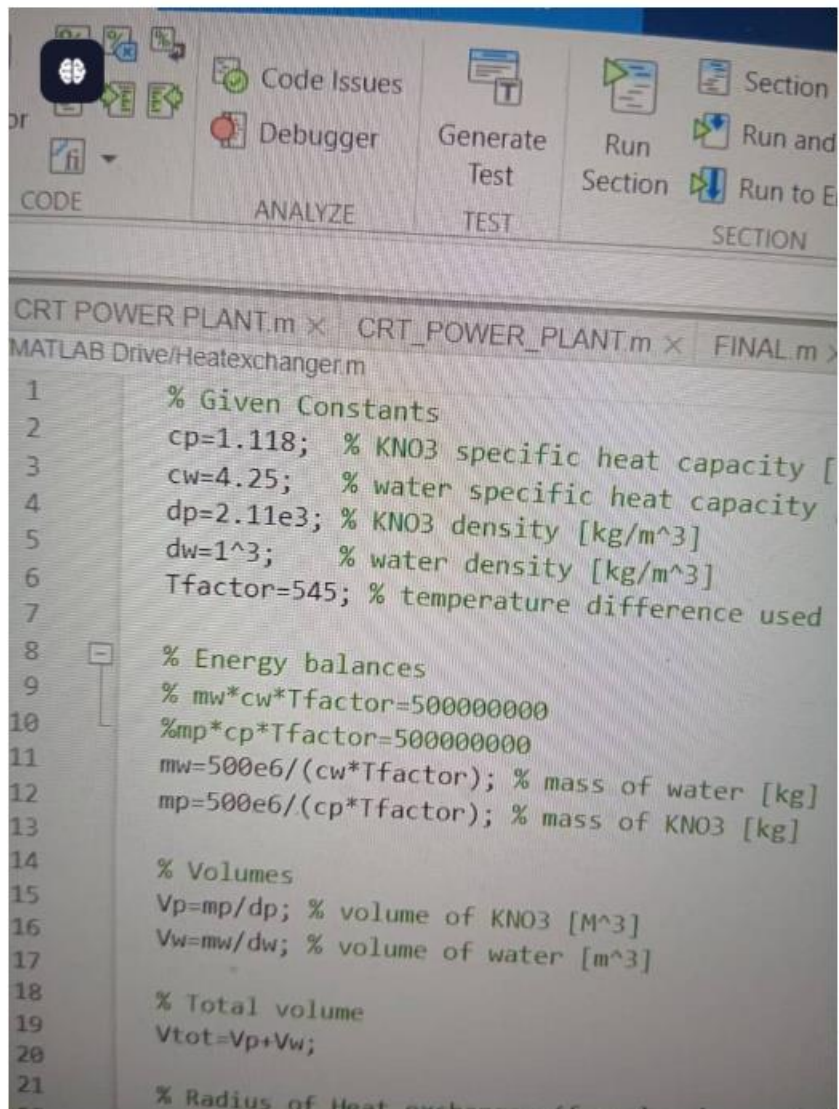
fprintf('Volume of KNO₃, $V_p =$ %.d m³\n', V_p);

fprintf('Mass of water, $m_w =$ %.3e kg\n', m_w);

fprintf('Volume of water, $V_w =$ %.d m³\n', V_w);

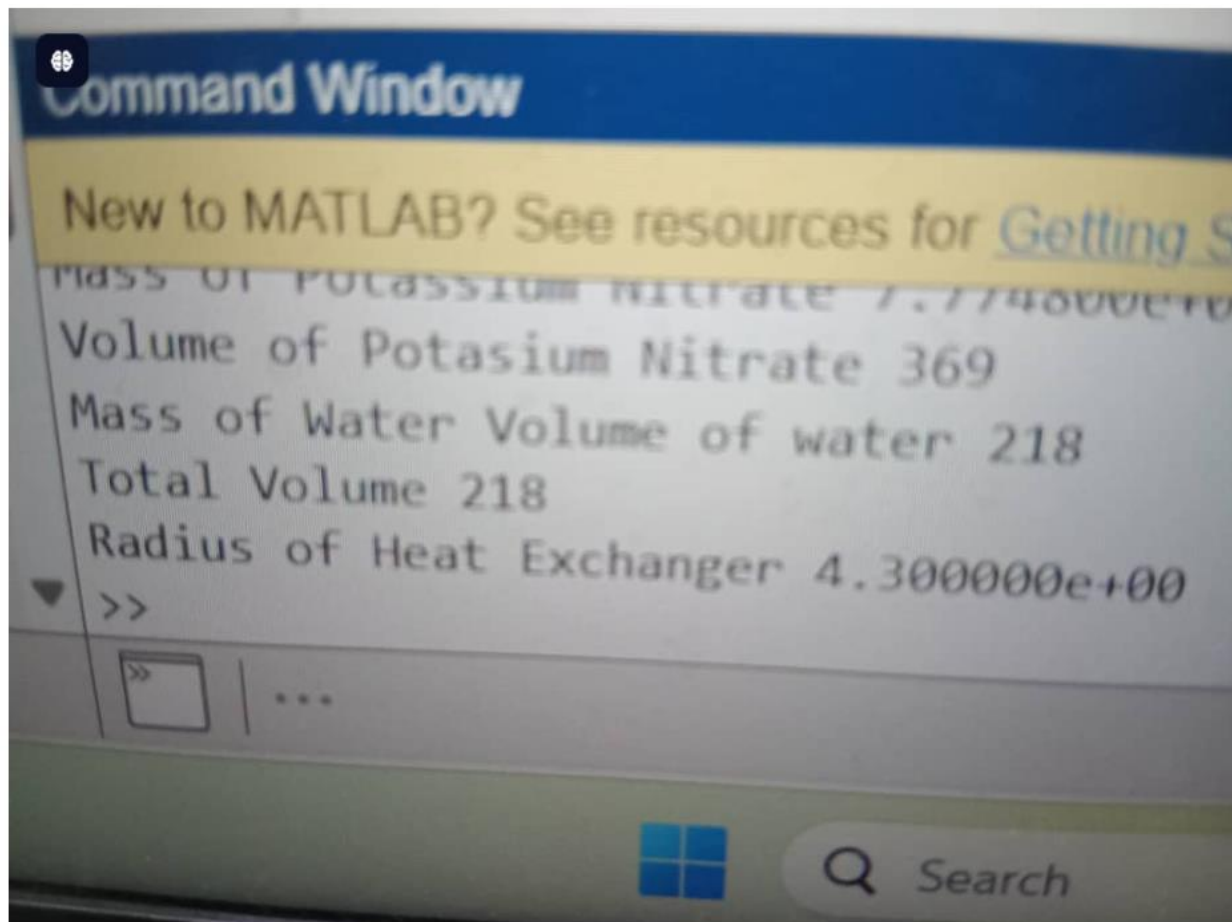
fprintf('Total volume $V_p + V_w =$ %.d m³\n', V_{tot});

fprintf('Heat exchanger radius $r =$ %.f m\n', r);



```
1 % Given Constants
2 cp=1.118; % KNO3 specific heat capacity [
3 cw=4.25; % water specific heat capacity
4 dp=2.11e3; % KNO3 density [kg/m^3]
5 dw=1^3; % water density [kg/m^3]
6 Tfactor=545; % temperature difference used
7
8 % Energy balances
9 % mw*cw*Tfactor=500000000
10 % mp*cp*Tfactor=500000000
11 mw=500e6/(cw*Tfactor); % mass of water [kg]
12 mp=500e6/(cp*Tfactor); % mass of KNO3 [kg]
13
14 % Volumes
15 Vp=mp/dp; % volume of KNO3 [M^3]
16 Vw=mw/dw; % volume of water [m^3]
17
18 % Total volume
19 Vtot=Vp+Vw;
20
21 % Radius of Heat exchanger (Formula)
```


OBTAINED RESULTS FOR DIMENSIONING A HEAT EXCHANGER



The obtained results agree with 4.3 m obtained using manual calculations

MATLAB SIMULATING PROGRAMME FOR CALCULATING HEIGHT OF TOWER ASSUMING IT NEEDS TO SUBTEND AN ANGLE OF 13.5° AT A HELLIOSTAT MIRROR 1000 M AWAY FOR ACCEPTABLE ATMOSPHERIC ATTENUATION

Computer Programme

% Height of Tower which should subtend an angle of 13.5° 100 meters away

% Configuration

distance = 1000; % in meters

angle_deg = 13.5; % elevation angle in degrees

% Compute height

height = distance * tand(angle_deg);

% Display result

fprintf('Height of tower: %.4f meters\n', height);



```
% CALCULATING THE HEIGHT OF A TOWER TO BE USED IN THE CRT PLANT

% Configuration
distance=1000; % in meters
angle_degree=13.5; %elevation for acceprable attenuation

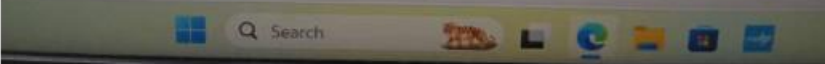
% Compute Height
height=distance*tand(angle_degree);

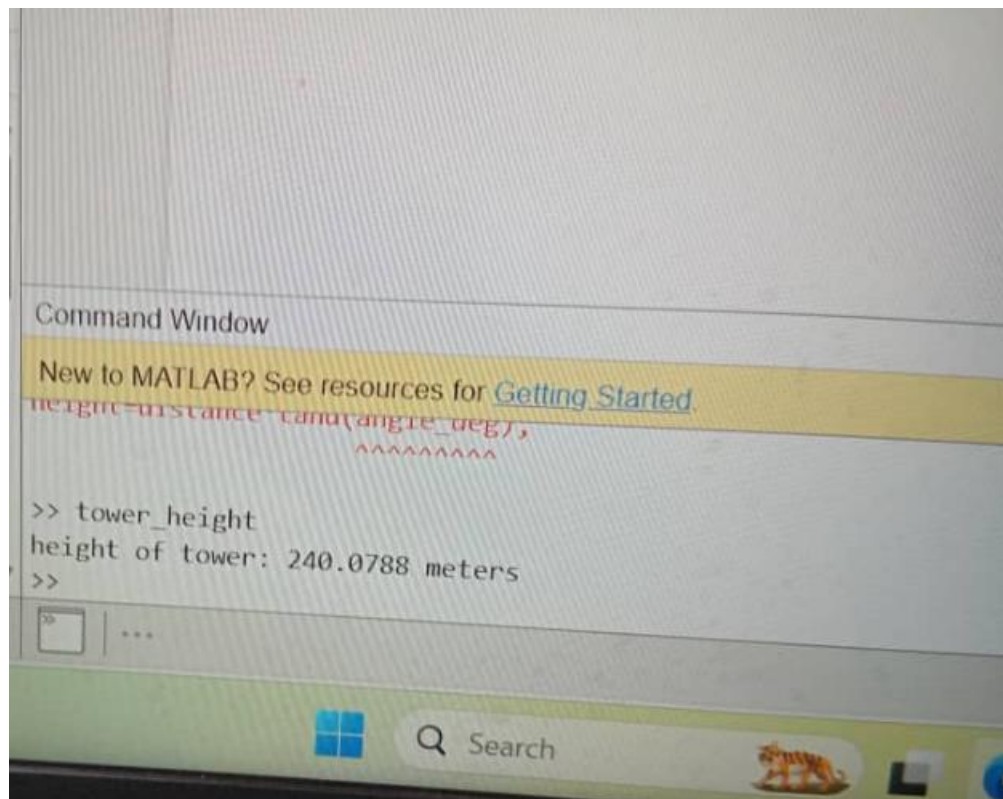
% Display Results
fprintf("height of tower: %.4f meters\n",height);
```

Command Window

How to MATLAB? See resources for [Getting Started](#)

```
height=distance*tand(angle_deg),
          ^^^^^^^^^
tower_height
height of tower: 240.0788 meters
```





The tower height according to the simulation=240m high

A Matlab computer coding software was used to simulate the overall plant output if the input power at the mirrors was 2 500 MW, assuming the following operational parameters below whose product was 20% were as follows:-

Optical efficiency =0.94

Shading and Blocking efficiency=0.8

Atmospheric attenuation=0.85

Tracking efficiency=0.8

Receiver Efficiency=0.99

Storage efficiency=0.99

Power Block Efficiency=0.76

The Matlab Simulating Code was as follows:-

```
% Simulating a Central Receiver Tower Power Plant
```

```
% Given
```

```
Solar_intensity_level=500 % MW/M2;
```

```
Input_power=2 500 000 000;
```

```
% Operational parameters
```

```
Shading_blocking_efficiency=0.8;
```

```
Atmospheric_attenuation=0,85;
```

```
Optical_efficiency=0.94;
```

```
Tracking_efficiency=0.8
```

```
Receiver_efficiency=0.99
```

Storage_efficiency=0.99

Power_block_efficiency=0.76

% Calculating overall efficiency

Overall_efficiency=shading_blocking_efficiency*atmospheric_attenuation*optical_efficiency*tracking_efficiency*receiver_efficiency*storage_efficiency*power_block_efficiency;

% Calculating the Area of mirrors Required(m^2)

Required_area_of_mirrors=Input_power/(Solar_intensity_level*overall_efficiency);

% Calculating Output Power Results

Output_power=overall_efficiency*Input_power;

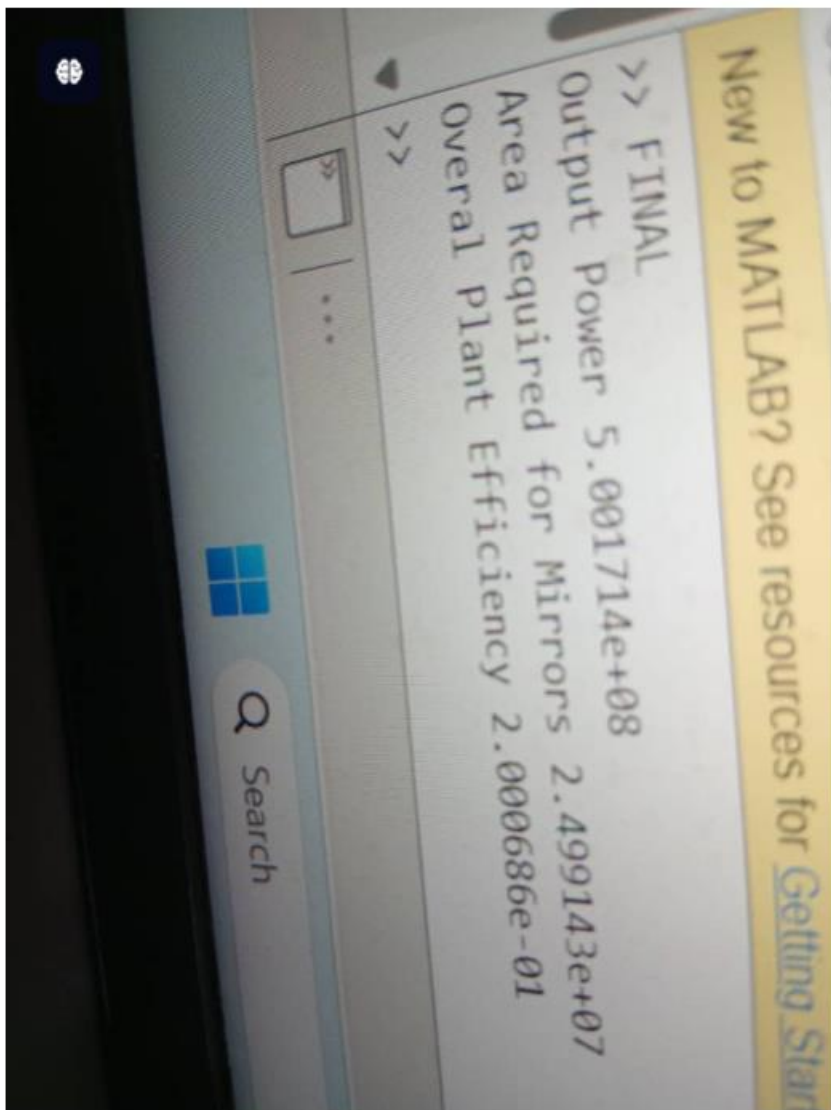
% Print Output

fprintf('Output Power %d \n',output_power)

fprintf('Area Required for Mirrors %d \n', required_area_of_mirrors)

fprintf('Overall Plant Efficiency %d \n', overall_efficiency)

The following results were obtained by running Matlab software. This validates that the output of the designed plant will be 500 MW (500 000 000 W)



```

1 % Simulating a Central Receiver Tower
2 % Given
3 Solar_intensity_level=500; % W/m2;
4 Input_power=25000000000;
5
6 % Operational parameters
7 shading_blocking_efficiency=0.8;
8 atmospheric_attenuation=0.85;
9 optical_efficiency=0.94;
10 tracking_efficiency=0.8;
11 receiver_efficiency=0.52;
12 storage_efficiency=0.99;
13 power_block_efficiency=0.76;
14
15 % Calculating overall efficiency
16 overall_efficiency=shading_blocking_eff
17
18 % Calculating the area of mirrors Required
19 required_area_of_mirrors=Input_power/(5
20
21 % Calculating Output Power Required

```

Command Window

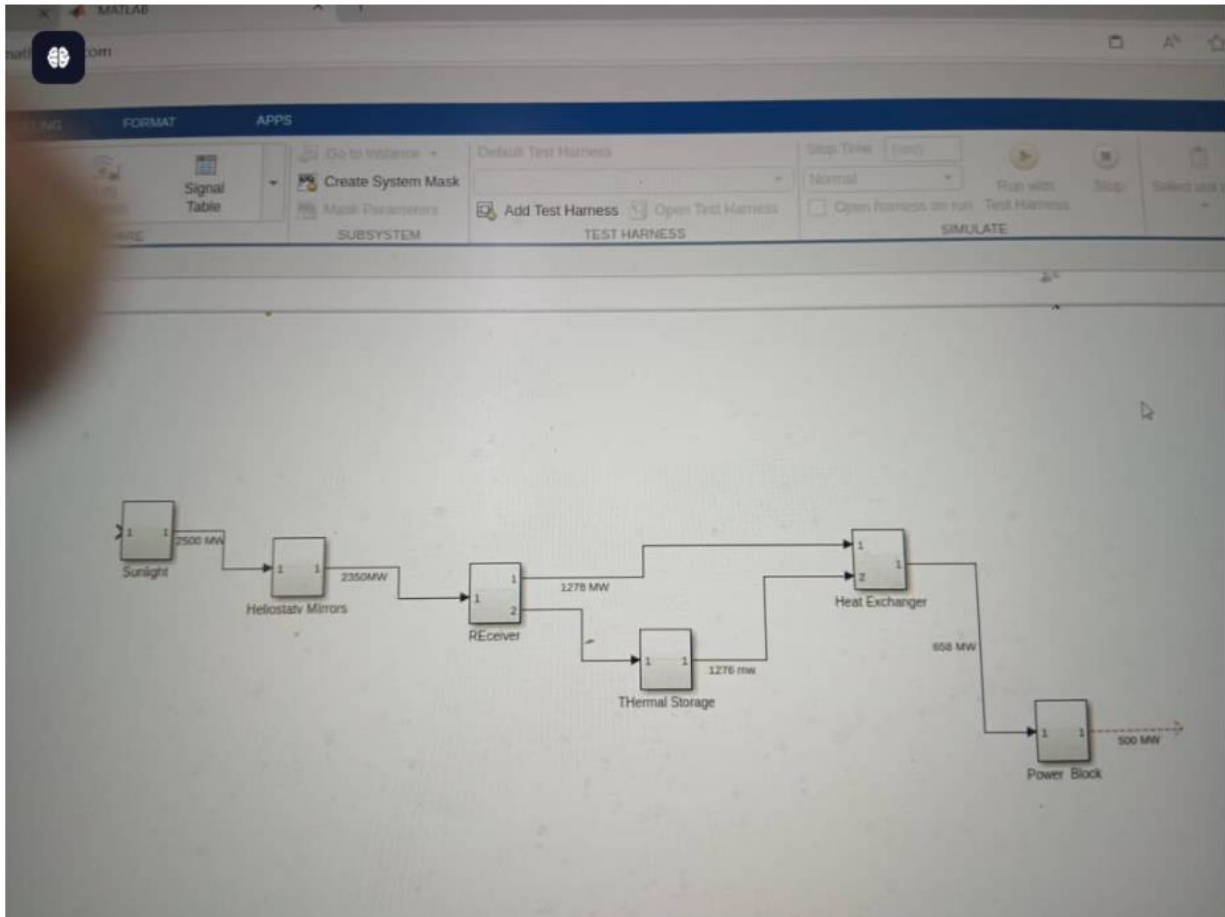
New to MATLAB? See resources for [Getting Started](#)

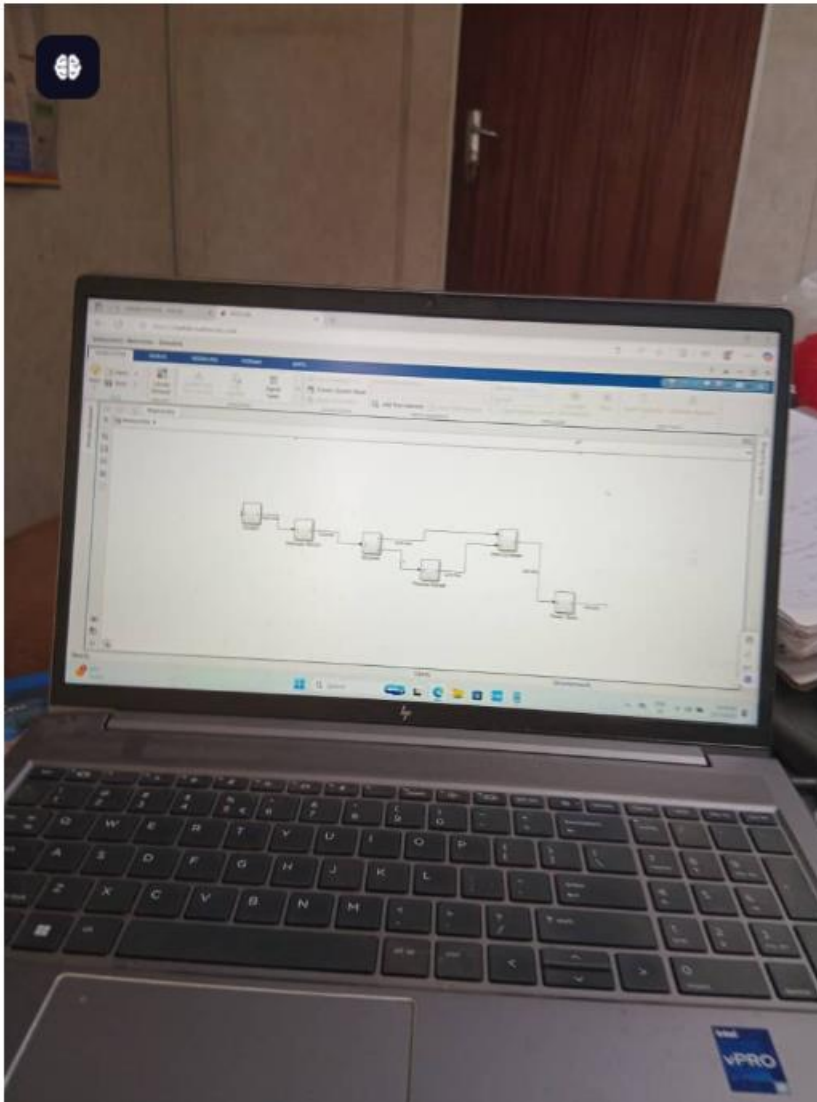
```

>> CRT_POWER_PLANT
Output Power 5.001714e+08
Area Required for Mirrors 2.499143e+07
Overall Plant Efficiency 2.000686e-01
>>

```


SIMULATION OF THE PLANT USING BLOCK DIAGRAMS IN MATLAB





AN ATTEMPT TO SIMULATE THE WHOLE PLANT-

%% CSP Plant Complete Design and Simulation in MATLAB

% Concentrated Solar Power Plant with Thermal Storage

% Components: Heliostat Field, Central Tower, Receiver, TES, Steam Cycle

% Author: Tendai Peter Munyanduri

% Date: 2025

clear all; close all; clc;

%% 1. PLANT DESIGN PARAMETERS

% =====

% Heliostat Field Parameters

heliostat.mirror_area = 140; % m² per heliostat

heliostat.reflectivity = 0.94; % Mirror reflectivity

heliostat.num_heliostats = 8000; % Total number of heliostats

heliostat.field_efficiency = 0.65; % Overall field optical efficiency

heliostat.tracking_power = 0.5; % kW per heliostat tracking power

% Central Tower Parameters

tower.height = 240; % m

tower.receiver_area = 1570; % m² (cylindrical receiver)

```
tower.receiver_absorptivity = 0.95; % Receiver surface absorptivity
```

% Thermal Energy Storage Parameters

```
tes.hot_temp = 565; % °C
```

```
tes.cold_temp = 290; % °C
```

```
tes.capacity_hours = 10; % Hours of full load storage
```

```
tes.efficiency = 0.95; % Round-trip efficiency
```

% Steam Cycle Parameters

```
steam.turbine_efficiency = 0.42; % Gross electrical efficiency
```

```
steam.rated_power = 110; % MW electrical output
```

```
steam.condenser_temp = 40; % °C
```

% Environmental Parameters

```
env.dni_rated = 950; % W/m^2 Direct Normal Irradiance
```

```
env.ambient_temp = 25; % °C
```

```
env.wind_speed = 5; % m/s
```

%% 2. HELIOSTAT FIELD MODEL

```
% =====
```

```
function [solar_power, field_efficiency] = heliostat_field_model(dni, sun_elevation,  
sun_azimuth, heliostat, time_hour)
```

```

% Calculate heliostat field performance

% Cosine factor (simplified model)
cosine_factor = max(0, sin(sun_elevation) * 0.8 + 0.2);

% Atmospheric attenuation (distance-dependent)
atm_transmission = 0.99 - 0.0001 * heliostat.field_efficiency * 1000;

% Shading and blocking losses (time-dependent)
shade_block_factor = 0.95 - 0.1 * abs(sin(2*pi*time_hour/24));

% Overall field efficiency
field_efficiency = heliostat.field_efficiency * cosine_factor * ...
    atm_transmission * shade_block_factor;

% Solar thermal power collected
total_mirror_area = heliostat.num_heliostats * heliostat.mirror_area;
solar_power = dni * total_mirror_area * heliostat.reflectivity * ...
    field_efficiency / 1e6; % MW thermal
end

%% 3. CENTRAL RECEIVER MODEL
% =====

```

```

function [receiver_power, receiver_temp] = receiver_model(incident_power,
mass_flow, inlet_temp, tower, env)

% Central receiver heat transfer model

% Heat losses (radiation and convection)
stefan_boltzmann = 5.67e-8; % W/m^2/K^4

% Radiation losses
receiver_temp_k = inlet_temp + 273.15;
q_rad = tower.receiver_area * stefan_boltzmann * tower.receiver_area * ...
    (receiver_temp_k^4 - (env.ambient_temp + 273.15)^4) / 1e6; % MW

% Convection losses (simplified)
q_conv = 0.002 * tower.receiver_area * (inlet_temp - env.ambient_temp) * ...
    sqrt(env.wind_speed) / 1000; % MW

% Net receiver power
receiver_power = incident_power * tower.receiver_absorptivity - q_rad - q_conv;

% Outlet temperature calculation (simplified)
cp_salt = 1.5; % kJ/kg/K for molten salt
if mass_flow > 0

```

```

    delta_t = receiver_power * 1000 / (mass_flow * cp_salt);
    receiver_temp = inlet_temp + delta_t;
else
    receiver_temp = inlet_temp;
end

% Temperature limits
receiver_temp = min(receiver_temp, 600); % Maximum allowable temperature
end

%% 4. THERMAL ENERGY STORAGE MODEL
% =====

function [tes_state, hot_tank_temp, cold_tank_temp, tes_power] =
tes_model(tes_state_prev, charge_power, discharge_power, tes, dt)

% Thermal energy storage model with hot/cold tanks

% Storage capacity in MWh
storage_capacity = steam.rated_power * tes.capacity_hours;

% Net power flow (positive = charging, negative = discharging)
net_power = charge_power - discharge_power;

```

```

% Update state of charge
tes_state = tes_state_prev + (net_power * tes.eta * dt);

% Apply limits
tes_state = max(0, min(tes_state, storage_capacity));

% Tank temperatures (simplified model)
soc_fraction = tes_state / storage_capacity;
hot_tank_temp = tes.cold_temp + soc_fraction * (tes.hot_temp - tes.cold_temp);
cold_tank_temp = tes.cold_temp;

% Actual storage power
tes_power = net_power;
end

%% 5. STEAM CYCLE AND POWER BLOCK MODEL
% =====

function [electrical_power, steam_flow] = power_block_model(thermal_power,
steam, env)

% Steam turbine generator model

% Temperature correction factor

```



```

temp_correction = 1 - 0.0005 * (env.ambient_temp - 15);

% Part-load efficiency correction
load_fraction = thermal_power / (steam.rated_power / steam.turbine_efficiency);
load_fraction = min(load_fraction, 1.0);

if load_fraction > 0.3
    part_load_factor = 0.8 + 0.2 * load_fraction;
else
    part_load_factor = 0.3;
end

% Electrical power output
efficiency = steam.turbine_efficiency * temp_correction * part_load_factor;
electrical_power = thermal_power * efficiency;

% Steam flow rate (simplified)
steam_flow = thermal_power * 3.6 / 2.5; % kg/s (approximate)
end

%% 6. CONTROL SYSTEM MODEL

% =====

```

```

function [control_signals] = control_system(solar_power, electrical_demand,
tes_state, storage_capacity)

    % Plant control logic

    control_signals = struct();

    % Storage dispatch strategy
    soc_fraction = tes_state / storage_capacity;

    if solar_power > electrical_demand

        % Excess solar - charge storage
        control_signals.charge_power = min(solar_power - electrical_demand, ...
            (1 - soc_fraction) * storage_capacity);
        control_signals.discharge_power = 0;
    elseif solar_power < electrical_demand && soc_fraction > 0.1

        % Deficit - discharge storage
        control_signals.discharge_power = min(electrical_demand - solar_power, ...
            soc_fraction * storage_capacity * 0.5);
        control_signals.charge_power = 0;
    else

        % No storage operation
        control_signals.charge_power = 0;
        control_signals.discharge_power = 0;
    end

```

```

end

% Heliostat field control

control_signals.field_focus = true; % Simplified - always focused when sun
available

% Receiver control

control_signals.receiver_active = solar_power > 10; % MW threshold

end

%% 7. PLANT SIMULATION MAIN FUNCTION

% =====

function results = simulate_csp_plant(duration_hours, time_step)

% Main simulation function

% Time vector

time = 0:time_step:duration_hours;

n_steps = length(time);

% Initialize result arrays

results = struct();

results.time = time;

```

```

results.dni = zeros(1, n_steps);
results.solar_power = zeros(1, n_steps);
results.electrical_power = zeros(1, n_steps);
results.tes_state = zeros(1, n_steps);
results.tes_power = zeros(1, n_steps);
results.efficiency = zeros(1, n_steps);

% Initial conditions
tes_state = steam.rated_power * tes.capacity_hours * 0.5; % 50% initial charge

for i = 1:n_steps
    current_time = time(i);
    hour_of_day = mod(current_time, 24);

    % Solar resource model (simplified daily pattern)
    if hour_of_day >= 6 && hour_of_day <= 18
        sun_elevation = sin(pi * (hour_of_day - 6) / 12) * pi/2;
        dni = env.dni_rated * sin(pi * (hour_of_day - 6) / 12) * ...
            (0.8 + 0.2 * rand()); % Add some variability
    else
        sun_elevation = 0;
        dni = 0;
    end
end

```

```

% Electrical demand profile (simplified)

electrical_demand = steam.rated_power * (0.7 + 0.3 * sin(pi * (hour_of_day -
6) / 12));

electrical_demand = max(electrical_demand, steam.rated_power * 0.3);


% Heliostat field

[solar_thermal_power, field_eff] = heliostat_field_model(dni, sun_elevation,
0, heliostat, hour_of_day);


% Control system

control_signals = control_system(solar_thermal_power, electrical_demand,
tes_state, steam.rated_power * tes.capacity_hours);


% Thermal energy storage

if i > 1

    [tes_state, ~, ~, tes_power] = tes_model(tes_state,
control_signals.charge_power, control_signals.discharge_power, tes, time_step);

else

    tes_power = 0;

end


% Available thermal power for electricity generation

```

```

    available_thermal = solar_thermal_power + control_signals.discharge_power -
control_signals.charge_power;

```

```

    % Power block

```

```

    [electrical_power, ~] = power_block_model(available_thermal, steam, env);

```

```

    % Store results

```

```

    results.dni(i) = dni;

```

```

    results.solar_power(i) = solar_thermal_power;

```

```

    results.electrical_power(i) = electrical_power;

```

```

    results.tes_state(i) = tes_state;

```

```

    results.tes_power(i) = tes_power;

```

```

    if solar_thermal_power > 0

```

```

        results.efficiency(i) = electrical_power / (dni * heliostat.num_heliostats *
heliostat.mirror_area / 1e6);

```

```

    else

```

```

        results.efficiency(i) = 0;

```

```

    end

```

```

end

```

```

end

```

```

%% 8. AUXILIARY SYSTEMS MODEL

```

```

% =====

```

```

function aux_power = auxiliary_systems_model(electrical_power, solar_power,
env)

    % Calculate auxiliary power consumption

    aux_power = struct();

    % Heliostat tracking power

    aux_power.tracking = heliostat.num_heliostats * heliostat.tracking_power / 1000;
    % MW

    % Heat trace and freeze protection (when not operating)
    if solar_power < 10
        aux_power.heat_trace = 2.0; % MW
    else
        aux_power.heat_trace = 0.5; % MW
    end

    % Cooling system (condenser fans)

    aux_power.cooling = electrical_power * 0.02; % 2% of electrical output

    % BOP systems (pumps, controls, lighting)

    aux_power.bop = 3.0; % MW constant

```

```

% Total auxiliary power

aux_power.total = aux_power.tracking + aux_power.heat_trace + ...
    aux_power.cooling + aux_power.bop;

end

%% 9. ECONOMIC ANALYSIS

% =====

function economics = economic_analysis(results, plant_parameters)

% Simple economic analysis

economics = struct();

% Annual energy production

annual_energy = sum(results.electrical_power) * (results.time(2) -
results.time(1)); % MWh

% Capacity factor

economics.capacity_factor = annual_energy / (steam.rated_power * 8760);

% Simplified cost model ($/MW installed)

capital_cost_per_mw = 4500000; % $4.5M/MW typical for CSP with storage

```



```

economics.capital_cost = capital_cost_per_mw * steam.rated_power / 1e6; % $M

% LCOE calculation (simplified)

economics.lcoe = economics.capital_cost * 1000 / (annual_energy * 25); %
$/MWh

fprintf('Plant Performance Summary:\n');
fprintf('Capacity Factor: %.1f%%\n', economics.capacity_factor * 100);
fprintf('Annual Energy: %.0f MWh\n', annual_energy);
fprintf('Estimated LCOE: $%.0f/MWh\n', economics.lcoe);
end

%% 10. MAIN SIMULATION EXECUTION

% =====

fprintf('Starting CSP Plant Simulation...\n');

% Run simulation for 3 days with 15-minute time steps
simulation_results = simulate_csp_plant(72, 0.25);

% Calculate auxiliary power consumption
aux_power_profile = zeros(size(simulation_results.time));
for i = 1:length(simulation_results.time)

```

```

    aux_power = auxiliary_systems_model(simulation_results.electrical_power(i), ...
                                        simulation_results.solar_power(i), env);

    aux_power_profile(i) = aux_power.total;
end

% Net electrical power
simulation_results.net_power      =      simulation_results.electrical_power      -
aux_power_profile;

%% 11. RESULTS VISUALIZATION
% =====

% Create comprehensive plots
figure('Position', [100, 100, 1200, 800]);

% Solar resource and thermal power
subplot(3,2,1);
plot(simulation_results.time, simulation_results.dni/1000, 'r-', 'LineWidth', 2);
hold on;
plot(simulation_results.time, simulation_results.solar_power, 'b-', 'LineWidth', 2);
xlabel('Time (hours)');
ylabel('Power/Irradiance');
legend('DNI (kW/m²)', 'Solar Thermal Power (MW)', 'Location', 'best');

```

```

title('Solar Resource and Thermal Collection');

grid on;

% Electrical power output

subplot(3,2,2);

plot(simulation_results.time, simulation_results.electrical_power, 'g-', 'LineWidth',
2);

hold on;

plot(simulation_results.time, simulation_results.net_power, 'k--', 'LineWidth', 2);

xlabel('Time (hours)');

ylabel('Electrical Power (MW)');

legend('Gross Power', 'Net Power', 'Location', 'best');

title('Electrical Power Generation');

grid on;

% Thermal energy storage

subplot(3,2,3);

plot(simulation_results.time, simulation_results.tes_state, 'b-', 'LineWidth', 2);

hold on;

plot(simulation_results.time, simulation_results.tes_power, 'r-', 'LineWidth', 2);

xlabel('Time (hours)');

ylabel('Storage (MWh) / Power (MW)');

legend('TES State of Charge', 'TES Power', 'Location', 'best');

```

```

title('Thermal Energy Storage Operation');
grid on;

% Plant efficiency
subplot(3,2,4);
plot(simulation_results.time, simulation_results.eta*100, 'm-', 'LineWidth',
2);
xlabel('Time (hours)');
ylabel('Solar-to-Electric Efficiency (%)');
title('Plant Efficiency');
grid on;

% Power balance
subplot(3,2,5);
plot(simulation_results.time, simulation_results.solar_power, 'r-', 'LineWidth', 2);
hold on;
plot(simulation_results.time, simulation_results.electrical_power, 'g-', 'LineWidth',
2);
plot(simulation_results.time, aux_power_profile, 'k:', 'LineWidth', 2);
xlabel('Time (hours)');
ylabel('Power (MW)');
legend('Solar Thermal', 'Electrical Output', 'Auxiliary Load', 'Location', 'best');
title('Plant Power Balance');

```

```

grid on;

% Storage state and charging/discharging
subplot(3,2,6);
yyaxis left;
plot(simulation_results.time, simulation_results.tes_state, 'b-', 'LineWidth', 2);
ylabel('TES State (MWh)');
yyaxis right;
bar(simulation_results.time, simulation_results.tes_power, 'r', 'BarWidth', 0.8);
ylabel('TES Power (MW)');
xlabel('Time (hours)');
title('Storage State and Power Flow');
grid on;

```

```

sgtitle('CSP Plant Performance Analysis', 'FontSize', 16, 'FontWeight', 'bold');

```

```

% Economic analysis

```

```

economics = economic_analysis(simulation_results, struct());

```

```

% Performance metrics

```

```

fprintf('\n=== CSP Plant Design Summary ===\n');

```

```

fprintf('Heliostat Field: %d heliostats, %.1f MW thermal peak\n', ...

```

```

    heliostat.num_heliostats, max(simulation_results.solar_power));

```

```

fprintf('Central Tower: %.0f m height\n', tower.height);
fprintf('Thermal Storage: %.1f hours capacity\n', tes.capacity_hours);
fprintf('Power Block: %.0f MW rated electrical\n', steam.rated_power);
fprintf('Peak Net Power: %.1f MW\n', max(simulation_results.net_power));
fprintf('Average          Daily          Efficiency:          %.1f%%\n',
mean(simulation_results.eta(simulation_results.eta>0))*100);

```

CHAPTER 8

6.0 COMPLETED WORK, AREAS FOR FURTHER WORK

The following were designed: -

1. The heliostat field
2. The tracking system
3. The tower
4. Thermal energy storage tanks
5. Control-room
6. Heat exchanger
7. The condenser
8. Turbine/generator set
9. Step up substation

A discussion of how to integrate solar with coal generation was undertaken and hence the objectives of the thesis were thus fully met. The various components of the Central Receiver Tower Power Plant were designed. At least 2 journal papers were published or were at Copyediting stage with the Journal of Technological Sciences at the time of binding this project. The site plan of the power station was drawn. All the research questions were answered and all objectives met in the process of implementing the project.

CONTRIBUTIONS TO WORLD BODY OF KNOWLEDGE

Contribution to the world body of knowledge includes (1) the fact that the thesis provides a comprehensive design for large scale solar thermal power plant and a practical framework for integrating with coal power stations. It will add both qualitative and quantitative value to the field of Renewable energy engineering in the context of Southern African countries like Zimbabwe (2) new methods of integrating solar and coal generation were proposed e.g coal pre-heat and solar post heat (b) solar pre-heat and coal post heat (c) parallel steam path to just before the turbine (d) parallel steam path and electricity generation with electricity busbars being the point of common coupling (e) different and separate coal and solar power stations many kilometers apart but feeding onto the same Zimbabwean electricity grid at 330 KV

Thermochemical heat storage requires a deep understanding of reaction dynamics and chemical kinetics i.e. speed of chemical reactions. We need to be able to capture a dimension which will enable us to measure the speed of a chemical reaction i.e. phase change or reversible endothermic reactions in thermochemical storage.

The 8 dimensions of chemical kinetics, their nomenclature and how to calculate them was done as further contribution to the world body of knowledge i.e. chromatic kinetics (from the word color), massionic kinetics (from the word mass), tastionic kinetics (from the word taste), Smellionic kinetics (from the word smell) and enthalpic kinetics (from the word enthalpy) and Phaseonic kinetics (from the word phase). When a chemical reaction occurs the products may experience changes in color, mass, taste, smell, phase, heat content (enthalpy) and phase from which the above names of the different reaction kinetics were derived. The author further added and defined the chromatic spectrum as further contribution to the world body of knowledge i.e. colorless=0, white=1, cream=2, yellow=3, orange=4, Pink=5, brown=6, purple=7, green=8, grey=9, black=10. The author further contributed to providing equations to quantify numerically chemical chromatic kinetics i.e. the speed of color change in a chemical reaction. The same was done for Smellionic kinetics and tastionic kinetics under Reaction dynamics and chemical kinetics. In Phaseonic kinetics Solid=1, liquid=2 and gas=3. The contribution to world body of knowledge was in giving names (nomenclature) to various dimensions of chemical kinetics and methods of

numerically quantifying them in numbers in terms of speed of the 5 of the 6 reaction kinetics. Enthalpic kinetics is the rate of change of heat content within the energy storage tanks or solar absorber. These constitute the 6 dimensions for analysis of chemical reaction kinetics

- Chemical kinetics can be analyzed by a 8 dimensional analysis as follows: -.

8 DIMENSIONAL ANALYSIS OF CHEMICAL KINETICS AND REACTION DYNAMICS (CONTRIBUTION TO WORLD BODY OF KNOWLEDGE- IN TERMS OF NOMENCLATURE AND CALCULATIONS)

- Chromatic kinetics = $\frac{(final\ color - initial\ color)}{time\ taken\ for\ the\ change}$
- Tastionic kinetics = $\frac{(final\ taste - initial\ taste)}{time\ taken\ for\ the\ change}$
- Smellionic kinetics = $\frac{final\ smell - initial\ smell}{time\ taken\ for\ the\ change!}$
- Enthalpic kinetics = $\frac{final\ enthlpy - initial\ enthalpy}{time\ taken\ for\ the\ change!} = \frac{mc\theta 2 - mc\theta 1}{time\ taken\ for\ the\ change!}$
- Massionic kinetics = $\frac{final\ mass - initial\ mass}{time\ taken\ for\ the\ change!}$
- Texturionic-kinetics = $\frac{final\ texture - initial\ texture}{time\ taken\ for\ the\ change!} = \frac{final\ roughness\ factor - intial\ roughness\ factors}{time\ taken\ for\ the\ change!}$

- Phaseonic kinetics = $\frac{\text{final phase} - \text{initial phase}}{\text{time taken for the change!}}$
- Soundiotic kinetics = $\frac{\text{final noise level(dB)} - \text{initial noise level(dB)}}{\text{time taken for the change!}}$

Sound level in Soundiotic kinetics is measured in decibels (Db)

Phase Change Spectrum

Solid=1, liquid=2, Gas=3

Literature says there are 3 states of matter as highlighted above, but this author would like to expand the phases into 5 states by expanding the solid state into 3 major states (a) rock-solid (b) powder and (c) paste, so the phase Spectrum will be as follows: -

Rock-solid=1, Powder=2, Paste=3, liquid=4 and gas=5, plasma=6

Phase change direction- gasification direction (from left to right) or solidifying direction (from right to left). Which makes it a vector. If direction of phase change is ignored it becomes a numerical scalar quantity

There are certain substances that cannot be classified as solid liquid or gas e.g. porridge or a flower paste which are hereby coined 'the paste or porridge' Phase. There are also substances which cannot be classified as either solid, liquid or gas for example mealie meal, flour or face powder in the women beauty industry which are hereby classified as being in the 'Powder' phase.

DRIVERS OF PHASE CHANGE

- (4) Temperature variations e.g. normal atmospheric, extreme temperature e.g. in a solar absorber or steel making furnace or ice cold.
- (5) Pressure variations or repeated, 'pressure shocks' e.g. in a mealie meal grinding mill in the food industry or stone crusher in the mining industry.
- (6) A combination of both temperature and pressure-hybrid causes

The above (i.e. the 5 states of matter & its spectrum) is also contribution to the 'World Body of Knowledge' within Chemistry under Latent heat storage

Solidifying or gasifying direction

- Total chemical kinetics=chromatic kinetics x tastionic kinetics x Smellionic kinetics x enthalpic kinetics
- **Two dimensional analysis of chemical kinetics**
- Chemical Kinetics=f(Spectrum Change, time, direction of change)=f(rate, direction)
- Total chemical kinetics=chromatic kinetics x tastionic kinetics x Smellionic kinetics x enthalpic kinetics x Phaseonic Kinetics x soundiotic kinetics x texturionic kinetic
- Where any of the Kinetics above does not change, the change is ignored in the above equation so that the equation does not equal zero=0

The Power System Planning Sciences' nomenclature was also enriched as part contribution to the 'World Body of Knowledge'.(nearizon planning-short term planning, averison planning –medium term planning and farison planning-long term planning)

Another contribution to the world body of knowledge was in the introduction of deformed steel bars in thermal energy storage tanks to act as fins in order to facilitate approach to uniform heat distribution throughout the tank.

- Solar tracking method which depends on finding the solar vector using 4 LDR which vector is transmitted to the heliostat mirror HC-12 radio transceiver and Arduino Mega software with absorber vector from each heliostat for calculating the normal vector for positioning the heliostat. Solar tracking for Central Receiver Tower power plants is a grey area in all literature reviewed and this project has illuminated that area.

- A manual, non-computer software design template and methodology of designing a 500 MW Concentrated Solar Thermal Power Plant specifically for Zimbabwe Kadoma was also done as contribution to world body of knowledge.

The project and thesis therefore significantly contributed to the ‘World Body of Knowledge.’

Areas for Future Research

1. How to increase competitiveness of Concentrated solar thermal power stations?
2. How to increase efficiency of CST plants, reduce generation, operation and maintenance costs?
3. What is the best Heat Transfer Fluid?
4. How to improve reflectivity of mirrors?
5. How to improve tracking technologies?
6. How to improve absorption efficiencies of solar receivers?
7. How to enhance Solar Tower Power Plants' protection, condition monitoring and operational intelligence.

How Research Can be Extended or Applied to Future Studies

- The research can be used as a basis or groundwork for future research as it provides a template or methodology of designing a Central Receiver Tower (CRT) power plant.
- The Research needs to be extended by researching on methods to improve overall plant efficiency and reducing capital costs of the CRT power plant

PRACTICAL AND POLICY IMPLICATIONS AND RECOMMENDATIONS

Vision 2030: says it wants Zimbabwe to move towards a prosperous and empowered Upper Middle Income Society by 2030 which can only be possible with adequate electricity. This project addresses the Infrastructural Development pillar for power on page 33 of the Vision 2030 document. This pillar prioritizes attainment of optimal generation of power from both Renewable and non-Renewable sources which entails generation expansion through development of new power stations. Vision 2030 aims to attain 95 % urban and 75 % rural electrification.

- There is need for meritocratic appointment policy in the power industry.
- There is need for a policy on the reduction of greenhouse gas emissions such as progressively closing down of coal power plants passing through solar-coal hybridization stages before total closure.

POLICY BARRIERS.

1. Meritocratic appointment policy in the power sector may not be followed as the ruling party will favour its supporters in critical appointments

2. Financial allocation policy may not adequately favour the power sector

How Studies Builds or Challenges Existing Knowledge

- Study builds on existing knowledge by providing a template or methodology of designing a Central Receiver Tower Power Plant
- Literature says there are 3 states of Matter, but studies challenges this perspective by highlighting 6 states of matter (1) rock solid (2) powder state (3) paste or thin porridge state (4) liquid (5) gas and (6) plasma

RECOMMENDATIONS

The single tower configuration was recommended because of cost consideration although a 5 tower leads to better efficiencies and smaller solar absorbers. For solar tracking, use of sensors e.g. photosensitive cells or use of chronological software can be employed to determine the sun vector. The solar absorber vector is constant and known for each heliostat and hence computers can calculate the bisector vector for positioning the heliostat using motors or hydraulic actuators. Hydraulic actuators use differential expansion of gases when subjected to different temperatures. A 30/330 KV step up substation or 30/88/132 kV substation is proposed for the site in order for the power station to feed into the existing nearby grid injection points.

CONCLUSIONS

The Central Receiver Power Tower power plant is the biggest CSP design in terms of geographical size comparing with all other CSP technologies. It comprises of a heliostat field that tracks a position suitable for focusing sunlight onto a stationary solar absorber throughout the day. The power tower power plant is expensive compared to other CSP technologies. It has high temperature efficiency which makes it a good candidate as a source of inexhaustible renewable energy and a good substitute for coal generation.

The design is a compromise between efficiency, needed electricity output and costs. Uranium-nickel cermet was selected to be the material for the solar absorber because of higher melting point. All the research questions were answered and all objectives met in the process of implementing this project. A Concentrated Solar Thermal Power Plant of the Central Receiver Tower Power Plant was thus designed, methods of integrating or hybridization with coal power plants demonstrated. Furthermore, there was contribution to the world body of knowledge on various fronts and areas. The scientific nomenclature was also greatly enriched by new names that were introduced in the thesis and given to new engineering dynamics, concepts and processes in this dissertation.

End.

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The Trapping Of Lightning Energy for Commercial Use-A Technical Paper	Copy-Editing Stage	Journal Of Technological Sciences	2024
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APPENDIX: PLAGIARISM REPORT SUMMARY



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